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SPREAD SPECTRUM RANDOM ACCESS SCHEMES

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Detailed investigations have been carried out on frequency-hopped spread spectrum-random access (SSRA) schemes in the presence of jamming, including control procedures for stable operation. Simulations also were carried out to verify and supplement the analytical results. It is shown that, unlike unspread systems, performance of a frequency-hopped packet communication network does not depend heavily on the burstiness of the user traffic or on whether slotted operation is used. Partial band and pulse jamming effects are modeled, and the possibility of successful reception of spreading code symbols with partial overlap is represented.

Static and dynamic control policies are considered for slotted ALOHA-SSRA schemes, with emphasis on the effects of the retransmission control policy. Performance of dynamic control is shown to be very robust in that it provides high throughput over wide ranges of arrival rates, unlike static control, which is highly sensitive to packet generation process and the chosen retransmission probability. A simple rule for computing the retransmission probability as a function of the backlog is provided

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and is very close to the analytically derived optimal function. It is also shown that dynamic control, which adaptively varies the transmission probabilities as a function of the network backlog and the jamming level, provides considerable performance improvement over static control when the jamming level is unknown or time-varying. Robust implementable dynamic transmission control policies are identified for single-hop slotted ALOHA-SSRA networks that do not require a "genie". Performance derived by simulation shows that it is nearly at the same level as that for a "genie" model that is derived by mathematical analysis of the underlying Markov chain.

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Preface

This report is concerned with the performance analysis of spread spectrum, both for its anti-jam protection and its multiaccess capability (through Code Division Multiple Access), and the use of spread spectrum in combination with random access schemes. Spread spectrum-random access (SSRA) networks are good candidates for the multi-user communications that may be needed in the SDI environment. During 1987-90, under the Strategic Defense Initiative Office (SDIO) Contract N-00014-87-C-0845, managed by the Office of Naval Research (ONR), we carried out detailed investigations on SSRA schemes in the presence of jamming, including control procedures for stable operation, error control, and traffic models. Simulations also were carried out to verify and supplement the analytical results.

The investigators would like to thank Dr. R.N. Madan of the Office of Naval Research for his enthusiastic support of this research and interest in the subject matter. They would also like to thank a number of their colleagues at the Rockwell International Science Center and other researchers in the field, too large a list to be mentioned here, for their comments and helpful discussions.

Publications

Papers from work performed under SDIO/ONR contract N00014–87–C–0845

1. L. P. Clare and A. R. K. Sastry, "The Effects of Slotting, Burstiness, and Jamming in Frequency-Hopped Random Access Systems," Conf. Record, pp. 154-160, IEEE MILCOM'89, Boston, October15-18, 1989.

2. L. P. Clare, J. E. Baker, and A. R. K. Sastry, "A Performance Comparison of Control Policies for Slotted ALOHA Frequency-Hopped Systems," Conf. Record, pp. 608-614, IEEE MILCOM'90, Monterey, October 1-3, 1990.

3. L. P. Clare and J. E. Baker, "The Effects of Jamming on Control Policies for Frequency-Hopped Slotted ALOHA," Conf. Record, pp. 1132-1138, IEEE GLOBECOM'90, San Diego, December 2-5, 1990.

4. L. P. Clare and J. E. Baker, "Robust Procedures for Implementation of Dynamic Control Policies for Frequency-hopped Slotted ALOHA," (in preparation).

Executive Summary

This report describes work on spread spectrum random access schemes under the SDIO contract N00014-87-C-0845 managed by the Office of Naval Research, during September 1987 - November 1990.

The communications needs for SDI involve survivable interconnections of a large number of nodes in both space and on ground with highly transient traffic characteristics and processing loads. The combined multiple access properties of random access protocols and spread spectrum techniques appear to be very attractive for meeting such SDI needs, as random access is very efficient at light traffic loads while spread spectrum smoothens the impact of congestion when traffic increases rapidly and provides anti-jam protection in addition to low probability of interception. While substantial amount of work is done by various researchers during the past two decades on both the unspread random access and on physical channel aspects of spread spectrum such as rapid code acquisition, modulation formats, filter and receiver structures, and estimation of probability of errors, very little has been done on link and network level protocol issues involved on a system that combines random access and spread spectrum schemes.

During the past three years we have made substantial progress in our investigations on this emerging topic under this contract. We have addressed such fundamental issues as comparison of slotted and unslotted schemes, control policies for stable operation, and performance evaluation under different jamming scenarios. Simulations also were carried out to verify and supplement the analytical results. A brief summary of the results obtained is given below.

1. **The Effects of Slotting, Burstiness, and Jamming in Frequency-Hopped Random Access Systems**: Performance of a frequency-hopped packet communication network is investigated. It is shown that, unlike unspread systems, performance does not depend heavily on the burstiness of the user traffic or on whether slotted operation is used. Partial band and pulse jamming effects are modeled and the possibility of successful reception of spreading code symbols with partial overlap is represented.

Jamming parameter values are determined that yield the greatest degradation as well as forward error correcting code rates that result in maximal information throughput.

2. **A Performance Comparison of Control Policies For Slotted ALOHA Frequency-Hopped Multiple Access Systems**: A performance analysis of slotted ALOHA with frequency-hopped code division multiple access is presented, with emphasis on the effects of the retransmission control policy. Static and dynamic control policies are considered. Performance using static control is shown to be highly sensitive to the relationship between the packet generation process and the chosen retransmission probability. Dynamic control, on the other hand, is very robust in that it provides high throughput over wide ranges of arrival rates. Delays are generally quite small when system parameters are properly set. A simple rule for computing the retransmission probability as a function of the backlog is provided and is very close to the analytically derived optimal value. Numerical performance evaluation is given for the case of a network of 250 users and a spread factor (number of hopping positions) of 100 and where the other system parameters are varied; numerous graphs illustrate the key concepts.

3. **The Effects of Jamming on Control Policies for Frequency-Hopped Slotted ALOHA**: A performance analysis of the effects of interference due to jamming on transmission control policies for slotted ALOHA with frequency-hopped code division multiple access is presented. Both static and dynamic control schemes are considered. With static control, the transmission probability is fixed, while dynamic control adaptively varies the transmission probabilities as a function of the network backlog as well as the interference level due to jamming. Dynamic control is shown to provide considerable performance improvement over static control when the interference level is unknown or time-varying. Performance is evaluated using both analytical and simulation models.

4. **Robust Procedures for Implementation of Dynamic Control Policies for Frequency-Hopped Slotted ALOHA**: Dynamic transmission control procedures are identified for single-hop slotted ALOHA networks using frequency-hopped spread spectrum for both code division multiple access and anti-interference. These control procedures are implementable, and do not require a "genie" as in earlier studies of such systems. Control is based on varying the probability of transmission as a function of the estimated network backlog (i.e., the number of users with packets pending). The backlog process is estimated by sensing activity on the receiver-based code while the user is not transmitting (half-duplex operation is assumed). The interference (ambient noise and/or jamming) is assumed to be statistically time invariant. Performance is

derived by simulation and compared to a "genie" model that is derived by mathematical analysis of the underlying Markov chain. Numerical examples show that the feasible system operates at nearly the same level of performance as the "genie" model, and that considerable robustness exists with respect to the accuracy of a priori knowledge of the interference level. Numerous graphs illustrate transient response and steady state behavior.

This report is divided into six chapters. Spread spectrum techniques and random access protocols, along with such issues as network stability are briefly described in chapter 1. The effects of burstiness of the traffic, time slotting of the channel, and jamming on frquency-hopped random access systems are presented in chapter 2. Dynamic and static control schemes for achieving stability are described and compared in chapter 3. The impact of jamming on the control procedures is discussed in chapter 4. A realizable dynamic control scheme is presented and analyzed in chapter 5. Concluding remarks and plans for future work are given in chapter 6.

Chapter 1

Introduction

Spread-spectrum techniques [1, 2] deliberately employ bandwidths that are much larger than the underlying information and are primarily used in military communications for security and for resistance to jamming and interference. They also offer increased reliability in the presence of multipath and frequency-selective fading. Performance of direct-sequence (DS), frequency-hopping (FH), and time-hopping (TH) types of spread spectrum techniques have been extensively investigated in the literature [1] considering a variety of jamming situations, modulation methods, and noise conditions. Spread spectrum techiques also lend themselves to multiple access in addition to providing secure and anti-jam communication. In this report, we concentrate on these multiple access properties, more specifically, random access applications.

1.1 Comparison Between Spread Spectrum and Fixed Assignment Schemes

Although spread spectrum is often used for anti-interference in a point-to-point link, it also finds great use in multiaccess/broadcast type media so as to utilize i inherent capability to partition the total communication channel resource so that multiple transmissions (to multiple receivers) may ta' place simultaneously. Each receiver is assigned a unique pseudo random (PN) sequence to realize the spread spectrum operation. The code set is to be chosen to meet low cross-correlation and high auto-correlation requirements [3, 4]. This capability of allowing simultaneous transmissions is referred to as Code Division Multiple Access (CDMA), and may be compared to other fixed assignment multiple access techniques, specifically Frequency Division Multiple Access (FDMA) and Time Division Multiple Access

(TDMA). However, CDMA is not as bandwidth efficient as FDMA or TDMA if the sole objective is to partition the communications channel into some fixed number of continuous subchannels. (Since the code set typically only yields quasi-orthogonal subchannels, some error correction is usually also needed.) Nevertheless, the anti-interference characteristics of spread spectrum in combination with its CDMA capability make it appealing.

If each individual user generates traffic in a bursty (high peak-to-average ratio) fashion, then each user should transmit information packets only when there is data to be sent. In packetized communication applications, synchronization of the PN code should be achieved at a receiver within a reasonable fraction of the packet length [1, 5] and with low false synchronization probability [6]. When communications among users in a multi-user channel is bursty, CDMA may be superior to fixed assignment TDMA or FDMA. The size of the user population may be far greater than the maximum number of simultaneous subchannels, and yet essentially all communications will be supported provided the number of active users at any instant is small enough. With such traffic requirements, it is proper to compare CDMA to demand-driven multiple access algorithms.

Often, in addition to communication between a fixed set of source-destination pairs, a true *networking* capability is required, i.e., the ability for each user to communicate among many possible destinations at different times. Demand-driven multiple access algorithms must therefore determine who has a message to send and to which destination, and resolve any possible contention among simultaneous demands, in addition to permitting the actual data transfer to take place. They can be divided into two basic types: Collision-avoidance protocols, such as token-passing, and random access protocols. Reservation schemes are also possible, in which the channel is partitioned into two parts, one for determining and resolving traffic demand, and the other for actual data transfer; the first part is achieved using presassignment, collision-avoidance or random access. It is the switching among source-destination pairs that requires us to consider CDMA in combination with another multiple access algorithm. We investigated spread spectrum in combination with random access schemes, since they are combined more naturally and are not as dependent on propagation delays as the collision-avoidance algorithms. Random access schemes are natural for consideration in combination with spread spectrum since packets that collide in time can be retrieved to some extent [7, 8, 9, 10, 11].

1.2 Random Access Techniques Relevant to SDI

The principal function of the SDI distributed processing/communications network is to support battle management through the boost, post-boost, mid-course, and terminal phases of

Ballistic Missile Defense. The SDI environment is expected to contain a great number of geographically dispersed nodes that must communicate substantial quantities of information within tight time constraints. Many of these nodes will be mobile, making full connectivity among the nodes very difficult to achieve. Thus, one can envision the SDI network as consisting of a number of subnetworks with a changing population of nodes. While it is conceivable that the subnet that each nonmanuevering node belongs to can be computed as a function of time, such computations would likely be prohibitive. The problem of subnetwork membership would be further exacerbated by the heavy attrition of nodes that can be expected. It seems clear that multi-access broadcast radio communications are needed at least for the interconnectivity of the space segment and for its connectivity to the terrestrial (ground, seafaring and airborne) elements. Random access schemes are most appropriate for the dynamic requirements indicated above and because of the large propagation delays that can be expected between network users. A variety of random access schemes are available. Two basic categories are the ALOHA-type schemes and the splitting (or tree) algorithms. Either class of schemes are further distinguished as to whether the network is synchronized (slotted) or not. In addition, either class may be used in conjunction with carrier sensing and possibly collision detection techniques. Selection from this array of choices is obviously quite involved and is basically guided by the broad system requirements and the underlying philosophy of dealing with issues such as whether the network should be centralized or distributed. Once a category of the access methods is chosen, several options within that category can be further examined. It appears that in an internetted SDI environment, several schemes may find application in different subnetworks. As a prelude to the description of our work in the subsequent chapters, different candidate random access schemes are briefly discussed below highlighting the features that are relevant for our work..

1.2.1 ALOHA Schemes

In the simplest of the random access schemes, generally now known in the literature as ALOHA schemes, a station transmits as and when it has a packet ready, which may collide in time with packets of other stations. Each station, if it has a collided packet, reschedules it for transmission after a random delay drawn from a distribution common to all the stations. The start times of the collective traffic from all such stations, consisting of the original and retransmitted packets, can be reasonably modeled by a Poisson point process. Theoretical results show [2, 12] that the system has a maximum channel utilization of about 0.184 when the packets have constant lengths. Since the starting times of the packets can be different, the collision intervals typically exceed the packet length and can even be of the length of several packets if more of them collide in a chain.

1.2.2 Slotted ALOHA Schemes

In a slotted ALOHA scheme, the start times of packet transmissions of all stations should coincide with the beginning of a time slot that is established through synchronization from a common clock. In this case, when two or more packets collide, they completely overlap in time. Theoretical analyses show that [2, 12] this can provide a maximum channel utilization of 0.368. The requirement of slot synchronization introduces the first element of complexity in the system compared to pure ALOHA, particularly if the nodes are mobile and thus have varying propagation delays among them. A centralized station serving as a reference synchronization control station may not be acceptable from the point of view of reliability. Even from the point of view of routing and flow control, a centralized approach may not be desirable. In a "stationless" approach, the slot timing reference is to be derived in a distributed manner meeting the degree of accuracy required. It should also be noted that the above results on maximum channel utilization are derived for an "infinite" number of users.

When positive ACKs are used, an ACK packet will have to be sent for every information packet that escapes collision and is received without errors. It can be seen that the volume of the ACK traffic would be substantial and could significantly influence the operation and performance of the random access process. Recent work on the subject shows that the presence of ACK packets will reduce the throughput of ALOHA-type schemes significantly compared to the throughput with information packets only [13, 14, 15]. However, when spread spectrum techniques are used, as shown in our preliminary analysis of Code Division Multiple Access (CDMA)-slotted ALOHA schemes [16], the impact of ACK traffic is much less severe. This is due to the fact that some of the collided packets can be recovered as a result of using CDMA.

For systems with a finite number of users, a Binomial distribution is a more appropriate model for the number of packets that arrive in a slot. As the number of users becomes fairly large, the Poisson assumption becomes more valid. Also, all the users are considered "identical" with regard to their packet generating characteristics. However, if the users do not have identical traffic characteristics, the maximum utilization would be somewhat higher than that for identical users, a phenomenon termed "excess capacity" [12] with regard to the allowable message rate partitions among the users. Thus the degree of nonhomogeneity in traffic rates should be considered in a network with a limited number of nodes and dissimilar traffic.

The communications capacity is maximized by requiring that all message transmissions are of equal length, but variable length transmissions are possible at lower capacity. Requiring all messages to have the same length is unrealistic, as message length will be a function

of the information contained, which is variable. One way around the fixed length constraint is to use ALOHA for a reservation subchannel, and then use a separate data channel on a reserved basis for the variable length messages. However, this approach is more susceptible to errors, particularly in a distributed control architecture, and more importantly, it requires an additional reservation delay. Thus it is likely that use of variable length messages on the random access channel is necessary to approach the optimal operation. The analysis of ALOHA schemes with variable lengths is quite complicated and often only bounds can be derived through approximate analyses [17, 18, 19].

1.2.3 Carrier Sense Multiple Access Schemes (CSMA)

In this scheme [2], each station "senses" or monitors the channel for any ongoing transmissions. Collisions can still occur if two or more stations sense the channel idle within a span of their relative propagation delay and transmit their packets. In a slotted system, sensing is done in a 'minislot' corresponding to the largest propagation delay. Several variations are possible depending on how the stations respond to the state of the channel. In the simplest case, known as the non-persistent CSMA, if a station finds the channel idle, it transmits a packet. If the channel is busy, it reschedules its transmission using a random delay drawn from a common delay distribution. In p-persistence CSMA, when a station finds the channel busy, it waits till the channel becomes idle. When it finds the channel idle, it transmits the packet with a probability p or delays it by a minislot with a probability $1 - p$. In both the cases, if a station's transmitted packet suffers collision, it reschedules the packet for retransmission after a random delay (and again goes through the cycle of sensing, etc.). In CSMA with collision detection (CSMA/CD) [20], if a station encounters collision during the transmission of a packet it suspends the transmission of the remaining portion of the packet and sends an erasure message.

The above CSMA algorithms may be considered as extensions to the ALOHA protocol in that a simple retransmission interval is chosen. As such, they are subject to the same stability problems (discussed further below). Recent work has been performed in applying ALOHA control procedures to the CSMA environment. Also, Virtual Time CSMA [21] essentially uses a sliding window mechanism used in some tree conflict algorithms, and offers improved performance.

The throughput–delay performance of CSMA or CSMA/CD is very sensitive to the ratio of the maximum propagation delay to the packet transmission time [2]. In addition, the requirement of carrier-sensing can lead to more jamming vulnerability in some applications, since the jammer may also sense the channel to effectively time his jamming signal so that messages can be interfered with at a high probability. This problem can be particularly severe

if the sensing is done at RF carrier level without the benefit of the security obtained through sensing after despreading a CDMA signal. Further, equipment delays due to modems, turn around times between transmit and receive modes, and processing times for implementation of higher level protocols can significantly reduce the effectiveness of CSMA in some practical situations. If these delays are large, their combined impact is such that the channel appears effectively as a high delay channel. When the delay corresponds to about a quarter of a packet transmission time or more, the CSMA performance worsens compared to that of ALOHA [2]. These considerations greatly restrict the possible applications of CSMA types of use in the context of SDI, especially SDI space segment applications.

1.2.4 Stability Considerations

In addition to the throughput and delay, stability is another dimension to the performance characterization of the contention based multiple access schemes. The statistical fluctuations in the traffic levels can cause a scheme to gradually drift into an unstable region of operation causing breakdown. Theoretical and simulation results for slotted ALOHA and CSMA show [22, 23, 24, 25] that for an "infinite population" (traffic independent of system state) the stationary stable operation does not exist over an extended time, while for a finite number of stations the performance can degrade to unusable levels in a time (called first exit time [22]) that depends on the mean retransmission delay. Dynamic control procedures have been derived using Markovian decision models for slotted ALOHA with a finite number of stations [23, 24] to keep the system stable. Only recently [26] have retransmission control schemes been devised that achieve stable ALOHA performance without constraints on the size of the user population (although, of course, the aggregate network traffic load is constrained). Accounting for the approximately Service-In-Random-Order (SIRO) nature of ALOHA, we have determined the exact delay performance under such a scheme [27]. With some modifications, the results can also be extended to CSMA schemes.

The ALOHA random access protocol has a number of virtues, such as simplicity in implementation and a consequent robustness to errors and dynamics. However, use of ALOHA can result in unstable behavior, causing low throughput and excessive delays, unless an adequate control procedure is employed. As part of the analysis of the spread spectrum-random access schemes, we define suitable control procedures to achieve stability. This effort made use of our previous work on defining and analyzing control procedures for the slotted ALOHA system without spread spectrum [28].

There are essentially two classes of methods for stabilizing the ALOHA system. In either case there is a chance that an individual transmission will fail, and the transmitting node must then decide when to attempt retransmission. The first class of methods bases

this decision solely upon acknowledgment information for the individual packet in question ("acknowledgment based transmission control"), whereas the second class of methods assumes that the decision can use feedback information about the entire network operation (referred here as "control based on global feedback"). The latter methods are preferable in that they are far superior in providing stable operation. However, global feedback may be more costly or infeasible to implement, *especially in the context of spread spectrum networks.* It is therefore important to consider both classes.

Early ALOHA schemes used static acknowledgment based control procedures, in which the delay until retransmission was always chosen from a fixed distribution. Bistable operation could occur, where one of the modes corresponds to low throughput and high delay, unless the offered traffic was sufficiently light. The definitions of stability proposed for this static case [22, 29] are highly dependent on the size of the user population. This type of control was assumed in the CDMA-ALOHA analysis of Joseph and Raychaudhuri [30].

More sophisticated acknowledgment based control schemes have been devised in which the retransmission delay ("back-off") depends on the number of collisions the packet has already suffered. Such control schemes are known to be unable to provide stability in the case where packet arrivals are independent of the system state ("infinite-user" model), as shown by Kelly [31] for polynomial back-off and by Aldous [32] for exponential (Ethernet) back-off. However, these schemes can be stable under more relaxed definitions of stability [33]. Also, greater stability can be achieved by forcing packets to be rejected (permanently lost) after some number of tries [34] (see also [35]).

Methods in which the control is based upon global feedback can provide stable operation, where stability is defined in the strong sense that the system is ergodic when the arrival process is state-independent (the so-called "infinite-user" assumption). Dynamic control procedures that achieve such stable slotted ALOHA performance have only recently been identified. Hajek and van Loon [26, 36] first defined a global feedback scheme and proved the existence of parameters that yield stable behavior. One of the authors of this report [28] defined another control scheme and derived formulas for determining that specific parameter values will yield stable operation.

Some extensions of global feedback based ALOHA control mechanisms to the spread spectrum environment have been proposed in the literature. A limited feedback (Success/Failure) version of Hajek and van Loon's scheme is considered in [37] (see also [38]). Hajek [39] considers a more specific feedback structure for a frequency hopped system, and offers a corresponding control mechanism. Other authors have considered feedback models used for tree types of random access protocols [40, 41]. Greater feedback can be obtained by properly integrating the random access strategy with the spreading code protocol. Related work in this area is given in [11, 42, 43].

Another aspect worth reiterating is our objective of analyzing unslotted types of random access algorithms, since it is apparent that there is relatively little to be gained in slotting the system given that spread spectrum is being used. Generally, little has been done in investigating control procedures and consequent stability measurements for unslotted systems. A related work is that of Molle [44], in which extension of tree algorithms to asynchronous (unslotted) operation is described.

1.2.5 Delay Analysis of Stable Spread Spectrum Random Access Schemes

The performance of a random access algorithm is characterized in terms of the delay suffered by packets until they are successfully received and the proportion of packets never delivered. When a control procedures are implemented in an ALOHA-type protocol, the determination of the delay–throughput performance becomes quite difficult, and usually required approximations based upon heuristics regarding the control process (*e.g.*, [45]). In [27] we derived an algorithm for computing the exact delay probability distribution for a broad class of dynamically controlled ALOHA protocols. This is the first time that the exact delay distribution (or even just mean delays) has been calculated for any dynamically controlled ALOHA protocol. A queueing analysis approach was employed and yields both transient and steady state performance. In particular, any *initial condition can be specified. Simulation* comparisons of alternative dynamic control procedures have been tabulated [28], which suggest that schemes of the type investigated will yield performance superior to alternative strategies.

1.2.6 Tree Algorithms

Another class of random access schemes are those where the contention is resolved using a tree algorithm [46, 44, 21, 47, 48]. In a Tree Algorithm [46], which normally assumes slotted operation, collisions are resolved by subdividing the stations into subgroups till a subgroup contains at most one transmitting station. Tree schemes are the most efficient algorithms known for resolving contention and can provide higher throughput than slotted ALOHA. Perhaps more importantly, unlike the ALOHA schemes, the tree schemes are inherently stable. In addition, for systems in which all users are synchronized to a common clock, a family of schemes has been developed [47] that are particularly efficient for time-constrained applications (such as the SDI environment).

Although tree schemes can achieve higher throughput than ALOHA, one must be careful about the robustness of the tree scheme in actual implementation. A case in point is the

"improvement" in capacity of the original Capatenakis scheme [46] by Massey [49]; Massey demonstrated that the "improved" scheme could deadlock in the presence of channel errors or unexpected user action. However, there are tree schemes that have been shown to be tolerant of system errors [50]. Dynamic control procedures for the ALOHA protocol must also be considered in an error-prone system. Recently, retransmission control schemes have been found for the ALOHA protocol that yield stable performance when the channel is subject to errors [51].

A number of additional issues exist. One aspect is the need for network synchronization (slotting). While the tree random access schemes typically assume a synchronized network, Molle [44] has shown that when the propagation delay is small this assumption can be relaxed by incorporating a "virtual clock" in each user node, and the resulting capacity is not reduced. Another issue is the requirement for all users to continuously monitor the activity on the channel, known as "full sensing," or whether a transmitter only needs to monitor the channel when it is attempting a transmission ("limited sensing"). Also, random access algorithms vary in their sensitivity to large propagation delays. Liu and Towsley [52] looked at interleaving methods for tree and window schemes and found that favorable throughput is obtained.

1.3 Spread Spectrum Random Access Schemes

The objective of this work was to study the performance of spread spectrum communications used in combination with random access algorithms. Such techniques are very attractive for supporting communications among mobile stations with bursty (high peak-to-average ratio) traffic. Random access schemes are natural for consideration in combination with spread spectrum since packets that collide can be retrieved to some extent [7, 8, 9, 10, 11]. Use of spread spectrum in random access schemes also allows superposition of acknowledgment traffic on the same channel with only a marginal degradation in the overall throughput.

In a bursty traffic setting, CDMA usually uses receiver-oriented codes, so that each receiver listens only for its particular code and any user wishing to communicate to it must transmit on that code. In this sense, CDMA operates much like FDMA; note that if multiple transmissions are made to the same receiver then a collision occurs.

Spread spectrum random access schemes can be implemented in a number of ways: slotted or unslotted, direct-sequence or frequency-hopped, fixed or variable packet sizes, static or dynamic DS/FH assignment, with or without co-channel acknowledgment traffic, etc. One of the most important aspects of combining spread spectrum and random access is the feedback available to the users for implementing the access control procedure and stabilizing

the network. As was pointed out previously, a common architecture will use receiver-oriented code assignment. If a collision occurs, only the individual receiver knows about it. However, many random access schemes require global feedback in order to yield stable operation. Since each receiver will be able to listen to only a fraction of the total band, it will have limited ability to derive estimates of the overall network behavior. Operation of the random access must be tolerant to errors in perception of the feedback, so that investigations in this area [51, 50] are particularly relevant.

A key objective in our work was to develop new, integrated performance measures that characterize both the anti-jam protection and the multiuser capability of spread spectrum random access schemes. Work has been done in deriving the CDMA capability in the presence of jamming [53, 54], however, in these analyses the number of simultaneous user transmissions is held constant. Analyses of SSRA systems with bursty traffic have used simple models of the jammer. For example, some authors model the jammer as being equivalent to some number of additional network users competing for random access. While this model simplifies the analysis, it is unlikely that it is very accurate.

The rest of this report is divided into five additional chapters. The effects of burstiness of the traffic, time slotting of the channel, and jamming on frequency-hopped random access systems are presented in chapter 2. Dynamic and static control schemes for achieving stability are described and compared in chapter 3. The impact of jamming on the control procedures is discussed in chapter 4. A realizable dynamic control scheme is presented and analyzed in chapter 5. Concluding remarks and plans for future work are given in chapter 6.

Chapter 2

The Effects of Slotting, Burstiness, and Jamming

Abstract

In this section, we study the effects of user traffic burstiness and jamming on both slotted and unslotted operation. It is shown that, unlike unspread systems, performance is not very sensitive to the burstiness of the user traffic, which implies that such a system is inherently well suited for supporting a random access protocol such as ALOHA. We also show that the there is little difference in performance between slotted and unslotted operation when spread spectrum is used. Both pulse and partial band jamming effects are investigated. The model allows for the possibility of successful reception of spreading code symbols with partial overlap.

2.1 Introduction

Many investigators have analyzed random access or continuous transmission in a spread-spectrum environment; a representative few are given by [55, 56, 57, 58, 9, 39, 10, 59, 60, 61]. Recent work [55] has shown that if the number of frequency bins q tends to infinity, then the throughput of an unslotted ALOHA system approaches that of a slotted system. In this chapter, we provide quantitative results that demonstrate the speed of this convergence, as well as simple approximations. Performance under both multiuser and jamming interference is also treated here; a related analysis is given in [56].

2.2 Spread Spectrum Random Access Model

The scheme we are considering employs code division multiple access (CDMA) in which transmitting nodes use different spreading codes in a frequency-hopped system. N users transmit over a common wide frequency band that is divided into q frequency bins (subchannels). A packet consists of L symbols that are transmitted serially with each symbol on a frequency bin chosen randomly according to a uniform memoryless pattern. We assume that there is no conflict due to multiple transmitters simultaneously sending data to the same receiver or due to half-duplex operation.

Both time-slotted and time-unslotted modes are considered. In the slotted mode, each transmission must begin on a network synchronization boundary, where the slot time is at least enough to transmit a packet. In the unslotted mode there is no such synchronization. In either case, we assume that network synchronization is not feasible at the symbol level.

We assume that the hop interval is equal to the dwell interval, and that a single data symbol is transmitted per hop. The hop interval is taken as the time unit. If two or more active transmitters choose the same frequency bin during overlapping symbol transmissions, then a "hit" occurs. A common model of symbol interference specifies that if any overlap occurs at all, then the symbol cannot be demodulated correctly. This model was generalized by Wieselthier and Ephremides [57] to allow for the possibility of correct demodulation in the presence of partial overlap, provided the overlap does not exceed some given value. In the presence of jamming, such a model appears to be mandatory, since otherwise a broadband jammer that places a miniscule jamming pulse in each dwell interval would destroy all communications with very little total average power; this is clearly unrealistic. We extend the symbol interference model of [57] to include the jammer as indicated in the symbol level performance characterization below.

We assume that there is a single jammer and it affects all receivers equally. The jamming alternates between ON and OFF. The duration of time that the jammer is ON is taken to be a constant. The OFF periods have exponentially distributed random lengths with given mean. When the jammer is ON, a contiguous subset of the q frequency bins are jammed. Each new jam pulse selects a different partial band from the preceding one (unless more than $q/2$ are jammed). Generally the jammer wishes to cause maximal interference subject to a limited overall proportion of time and frequency that the jammer occupies.

The receiver is assumed to have perfect side information, so that a symbol is either received correctly or is erased. Each packet is a single extended Reed-Solomon (L, k) code word. Up to $L - k$ symbol erasures can be tolerated in a packet. Denoting by H the number of erasures, $P(\text{Packet Erasure}) = P(H > L - k)$.

Summarized below is the notation used in the mathematical model that applies to both

the analytical and the simulation investigations.

System characteristics

q = the number of frequency bins (spreading factor).

γ = the maximum proportion of a symbol that can be overlapped with interference without corrupting the correct reception of the symbol (see τ_I).

User characteristics

N = the number of users that can transmit.

L = the fixed packet length of a user transmission, measured in symbols.

δ = the mean proportion of time that an individual user is actively transmitting. All users are assumed to generate transmissions independently and with identical statistics. $\delta = L/(L + E(I_U))$ where I_U = user idle time between transmissions (exponentially distributed).

$\mu = N\delta$ = aggregate offered user traffic load.

$\ell_U = \mu/q$ = aggregate offered load per frequency bin.

k = number of information symbols in (L, k) Reed-Solomon code.

Jammer characteristics

ρ_f = proportion of the q frequencies that are jammed when the jammer is active.

ρ_t = proportion of time that the jammer is active.

a = the fixed length of the jam pulse during which the jammer is active, measured in units of symbol times. This need not be an integer.

$\ell_J = \rho_f \rho_t$ = normalized jammer "load" (or intensity) per frequency bin. $\rho_t = a/(a + E(I_J))$ where I_J = jammer idle time between pulses.

Performance Characterization: Symbol Level

τ_U = proportion of a symbol (in time) that overlaps one or more other users' symbols that fall in the same frequency bin.

τ_J = proportion of a symbol that overlaps a jamming pulse that falls in the same frequency bin.

τ_{UJ} = proportion of a symbol that overlaps both a jamming pulse and one or more other users' symbols that fall in the same frequency bin.

$\tau_I = \tau_U + \tau_J - \tau_{UJ}$ = interference suffered by a symbol. A symbol is erased if and only if $\tau_I > \gamma$.

Performance Characterization: Packet Level

H = the number of symbols hit (and erased) in a packet. $0 \leq H \leq L$.

S = information throughput per frequency bin = $\ell_U \frac{k}{L} P(H \leq L - k)$.

S_{agg} = aggregate information throughput = Sq.

2.3 Analysis

2.3.1 Analysis for bursty traffic and no jamming

We first treat the bursty traffic case ($\delta \ll 1$ and $N \gg 1$). This corresponds to packet transmission arrivals forming a rate μ Poisson process. In the case of slotted operation, an analogous discrete-time arrival process is applicable. We assume no jamming, and $\gamma = 0$.

Consider the probability that a randomly chosen symbol is hit. Let X denote the number of other transmissions ongoing; since a symbol duration is short, we assume that X is constant during the symbol transmission. If the system is operating in slotted mode, then one can show that X is a Poisson random variable of rate μ. If the system is unslotted, then from queueing theory we know that the number of active transmitters corresponds to the number in a $M/G/\infty$ system, which is also a Poisson (μ) random variable. Thus the hit probability is the same in either case.

Each interferer has an independent probability $(1 - 1/q)^2$ of not choosing the same frequency slot as that of the selected symbol, so that $P(\text{selected symbol succeeds} \mid X = i) =$

$(1-1/q)^{2i}$. Unconditioning on X,

$$P(\text{selected symbol succeeds}) = \exp[\mu(\frac{1}{q^2} - \frac{2}{q})]. \tag{2.1}$$

Now we consider a randomly selected packet. Let $K_\ell = 1$ denote the event that the ℓ^{th} symbol in the packet is hit. The expected number of hits in the packet is $E(H) = \sum_{\ell=1}^{L} P(K_\ell = 1) = LP(K = 1)$, where the latter equality uses the fact that the events $\{K_\ell = 1\}$ are disjoint and identically distributed (although they are correlated). Using (2.1),

$$E(H) = L\Big\{1 - \exp[\mu(\frac{1}{q^2} - \frac{2}{q})]\Big\}. \tag{2.2}$$

Note that this result for $E(H)$ applies to either slotted or unslotted operation! However, the distribution functions for H are different for the two systems, due to the correlation among the random variables $\{K_\ell, \ell = 1, \ldots, L\}$. Define X_ℓ to be the number of interferers during the ℓ^{th} symbol. In slotted operation, all of the X_ℓ's during a given packet are identical. In unslotted operation, less dependency occurs between the X_ℓ's and hence less among the K_ℓ's. The impact is that there tends to be larger variance in the number of hits H in slotted operation than in unslotted operation, although our simulation results have shown that the difference quickly diminishes with increasing q. These issues are critical to determining the optimal forward error correcting code.

In the slotted case, the complete distribution function for H can be found by assuming the symbol hit events, given X, are i.i.d. with hit probability $r = r(X) = 1 - (1-1/q)^{2X}$. We can then uncondition on X to obtain

$$\begin{aligned} P(H=h) &= E[\binom{L}{h} r^h (1-r)^{l-h}] \\ &= \binom{L}{h} \sum_{x=0}^{\infty} [1-(1-\frac{1}{q})^{2x}]^h (1-\frac{1}{q})^{2x(L-h)} \frac{\mu e^{-\mu}}{x!}. \end{aligned} \tag{2.3}$$

In the unslotted case, the number of interferers $X(t)$ during the chosen packet's transmission evolves, with a mean of $q\ell_U/L$ new arrivals and a similar number of departures occurring during one symbol duration. Thus we expect the correlation between $X(t)$ and $X(t+1)$ to $\to 0$ as $q \to \infty$ (fixed ℓ_U/L). We therefore approximate the unslotted case by modeling the X_ℓ's as being independent Bernoulli variables with

$$P(K_\ell = 1) = \bar{r} = 1 - \exp[\mu(-2/q + 1/q^2)], \tag{2.4}$$

and H is binomial with parameters L and $\bar{r}$:

$$P(H = h) = \binom{L}{h} \bar{r}^h (1 - \bar{r})^{L-h}. \tag{2.5}$$

Evaluation of the above hit distributions will be presented in the next section in combination with simulation results. These show that the distribution function for the unslotted case is closer to that of the slotted model than to the independence model. In terms of ℓ_U, (2.1) implies that $P(K = 0) = \exp[\ell_U(1/q - 2)]$, which decreases from $e^{-\ell_U}$ at $q = 1$ to $e^{-2\ell_U}$ as $q \to \infty$. Therefore, for slotted or unslotted operation,

$$\lim_{q \to \infty} E(H) = L(1 - e^{-2\ell_U}). \tag{2.6}$$

More generally, one may take the limit of the distribution functions for the slotted case and the independence model and show that they both converge to a binomial distribution with parameters L and $1 - e^{-2\ell_U}$. Since the unslotted case is believed to lie between the slotted and independence model cases, we conclude that the slotted and unslotted systems yield equivalent performance as $q \to \infty$ with ℓ_U fixed.

Note that when unslotted operation is used, one may relax the requirement that L is constant. The results for $E(H)$ depend only on the mean of the packet length L, since the distribution of the number in an $M/G/\infty$ system depends only on the mean of the service distribution G.

2.3.2 Jamming analysis

Consider the case where the jamming signal pulse length $a \gg 1$, and the jammer intensity ℓ_J is fixed. If a symbol is jammed then it is generally jammed during the entire symbol duration, so that γ does not play a role as far as the jammer is concerned. Suppose a single user is transmitting continuously. We assume the following rules for the game: (1) The jammer is constrained to a fixed value of ℓ_J. (2) The jammer can choose ρ_f and ρ_t arbitrarily, subject to $\rho_f \rho_t = \ell_J$ and $0 < \rho_f, \rho_t \leq 1$. (3) The user is free to choose the coding parameter k. (4) The user knows ρ_t and ρ_f, so that the code rate is chosen to maximize throughput subject to these jamming parameters. (5) The jammer knows that the user knows whatever values of ρ_t and ρ_f are chosen, and chooses these parameters so as to minimize the user's throughput. Thus, a minimax throughput results.

Choose a packet at random and consider the probability of successful receipt. Since $a \gg 1$, with high probability the jammer does not change state during the entire packet transmission. If the jammer is OFF, which occurs with probability $1 - \rho_t$, the packet surely

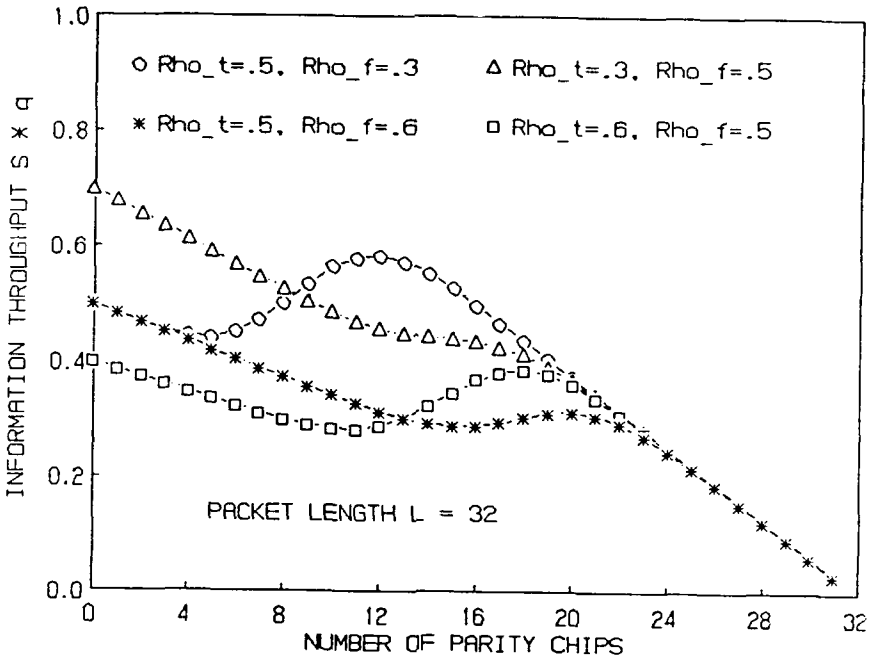

Figure 2.1: Total information throughput S_{agg} for single user versus number of parity symbols

is successfully received. If the jammer in ON, then each of the L symbols will be jammed depending on whether they fall within the partial band being jammed. The number of hit symbols H in the jammed packet is therefore binomially distributed with parameters L and ρ_f. The information throughput for a randomly chosen packet is then

$$S_{\text{agg}} = \frac{k}{n}[(1-\rho_t) + \rho_t P(H \leq L-k)]. \tag{2.7}$$

Example computations of S_{agg} versus the number of parity symbols $L-k$ are presented in Figure 2.1, where ρ_t and ρ_f are fixed and $L = 32$. A bimodal characteristic often appears. If no parity is used, the effect of the jammer is the same for the cases $\rho_t = .5$, $\rho_f = .3$ and $\rho_t = .5$, $\rho_f = .6$, even though ℓ_J differs by a factor of 2 for for these cases. The use of no parity maximizes throughput in the case $\rho_t = .5$, $\rho_f = .6$, but significantly higher throughput is obtained in the $\rho_t = .5$, $\rho_f = .3$ case when 12 parity symbols are used.

Figure 2.2 depicts performance when $\ell_J = 1/8$ and ρ_f and ρ_t are varied. $L = 64$ is

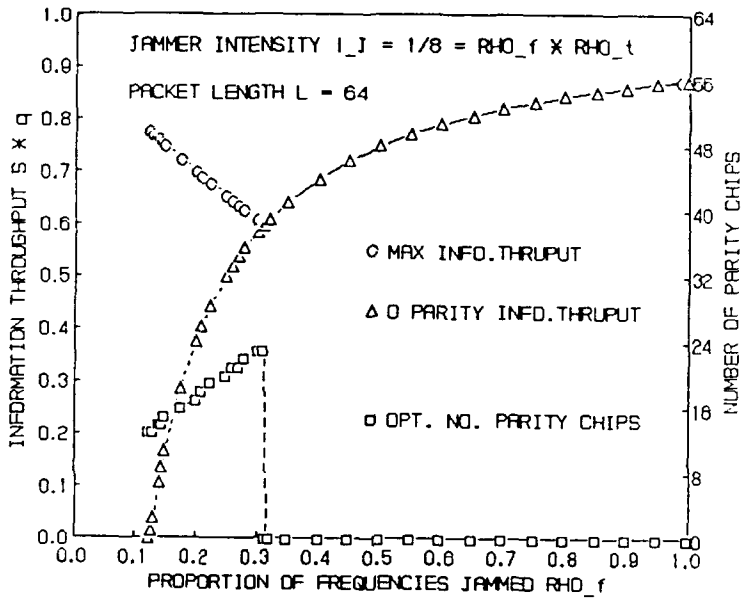

Figure 2.2: Total information throughput S_{agg} for single user vs. proportion of jammed frequencies ρ_f

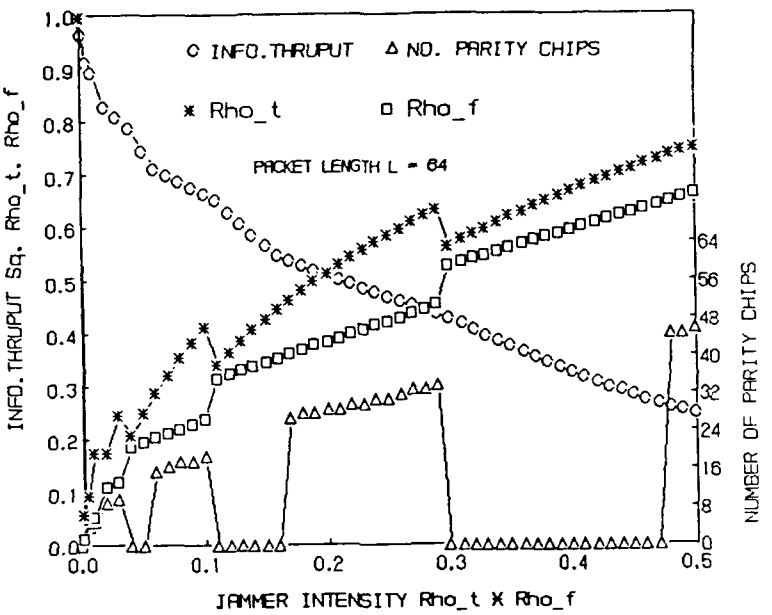

Figure 2.3: Minimax information throughput and optimal parameter values vs. jammer intensity ℓ_J

assumed. If $k = L$, then the throughput is 7/8 when $\rho_f = 1$ and $\rho_t = 1/8$, and decreases to nearly zero as ρ_f is decreased to 1/8 and ρ_t is increased to 1. However, for ρ_f less than .31 the user can obtain greater throughput by forward error correction. Under the assumption that the user knows the jammer parameters and thereby selects the best code rate, the jammer should choose $\rho_f = .31$ and $\rho_t = .4$ to minimize the user's throughput.

Figure 2.3 extends this example for a range of jammer intensity values. Only the minimax performance is shown. The values were derived as follows: For given ρ_t and ρ_f, find k that maximizes S_{agg}. Do this for each pair of ρ_t, ρ_f such that $\rho_t \rho_f = \ell_J$ for constant ℓ_J, and determine which such pair yields the minimum (minimax) S_{agg}. This was done for all $\ell_J \in [0, .5]$. The optimal strategies for the jammer (ρ_t, ρ_f) and user $(L - k)$ are shown as well as the resulting S_{agg}.

Two important points should be noted. First, the optimization here is with respect to information throughput only. Secondly, in our model a symbol that is completely overlapped

by a jamming pulse is surely erased. Other models allow for the possibility that such a symbol can still be correctly demodulated with some positive probability.

Next consider the case where the jam pulse length is very small ($a \ll 1$) and we no longer restrict ourselves to a single user. In such a situation, each symbol will be hit many times by the very short pulses, with the mean amount of overlap being ℓ_J and an overlap variance that decreases as $a \to 0$. Therefore, in the limit, each symbol suffers very close to ℓ_J jammer overlap in addition to whatever usual overlap is caused by multiuser interference. Clearly, if $\ell_J > \gamma$ then essentially every symbol will be erased. If $\ell_J < \gamma$ then there may be sufficient multiuser interference to cause symbols to be erased, however, we intuitively expect to see a quick drop in jammer effectiveness as ℓ_J passes below γ. In the numerical examples to be shown in the next section it will be seen that the jammer pulse length should not fall below γ in the case $\ell_J < \gamma$ if the jammer wants to minimize user throughput.

2.4 Simulation

A simulation model has been developed for the spread spectrum system that was defined in Section 2.2. The simulation provides histograms that reflect the probability distributions for the symbol-level interference variables τ_U, τ_J and τ_I, as well as the packet-level variable H. The simulation uses the distribution of H to compute the normalized information throughput S for each possible number of information symbols k out of L, and the maximizing code rate is identified along with the maximum information throughput.

2.4.1 No jamming.

Figure 2.4 presents the probability distributions for the number of hits H per packet for the slotted and unslotted frequency hopped systems in which there is no jamming, no tolerance of partial overlap ($\gamma = 0$), $L = 64$, $\ell_U = .25$, and $N = 100$ bursty users. Both analytical and simulation results are shown. For brevity, only the case $q = 64$ is shown. This demonstrates that at this moderate value of q there is already very close agreement between the the various distributions. As expected, the performance for the unslotted case lies between that of the slotted and of the independence model.

Figure 2.5 presents the hit distributions of the unslotted case with $\ell_U = .25$ or $\ell_U = .025$ and with various values of q; the parameters are otherwise the same as for the previous figure. This shows how the number of hits becomes probabilistically more concentrated as $q \to \infty$, although the mean number of hits does not vary significantly. This implies that when q is large, a forward error correcting code that can correct just slightly more than the

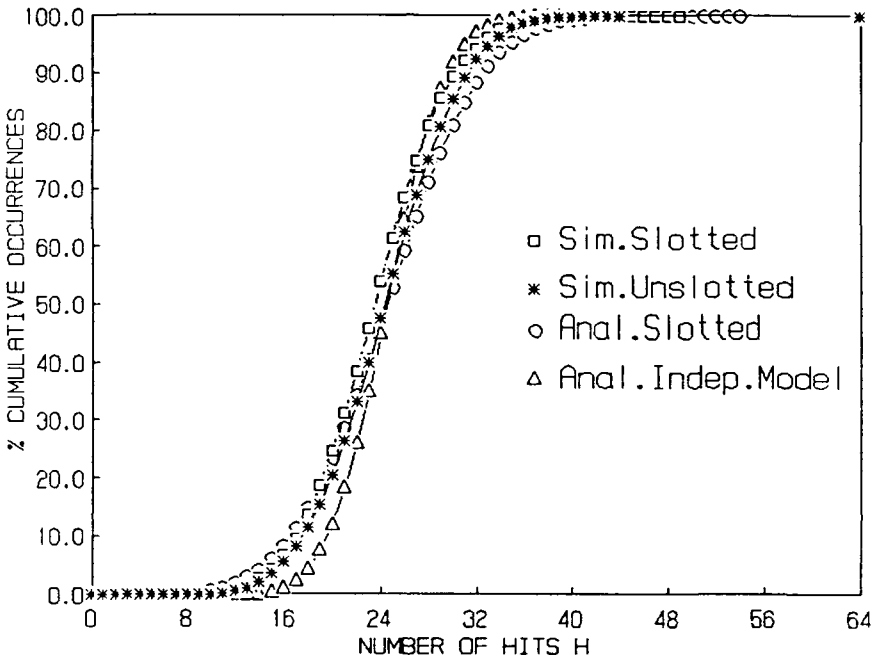

Figure 2.4: Probability distributions of the number of hits per packet $P(H \leq h)$, $q = 64$ and $\ell_U = 1/4$

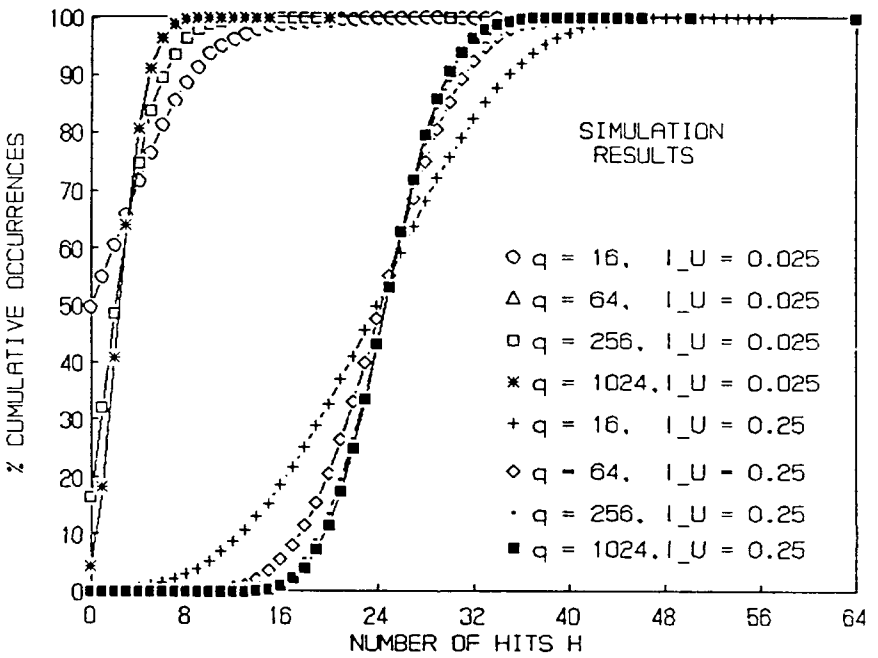

Figure 2.5: Probability distributions of the number of hits per packet, unslotted case, $q = 16, 64, 256, 1024$

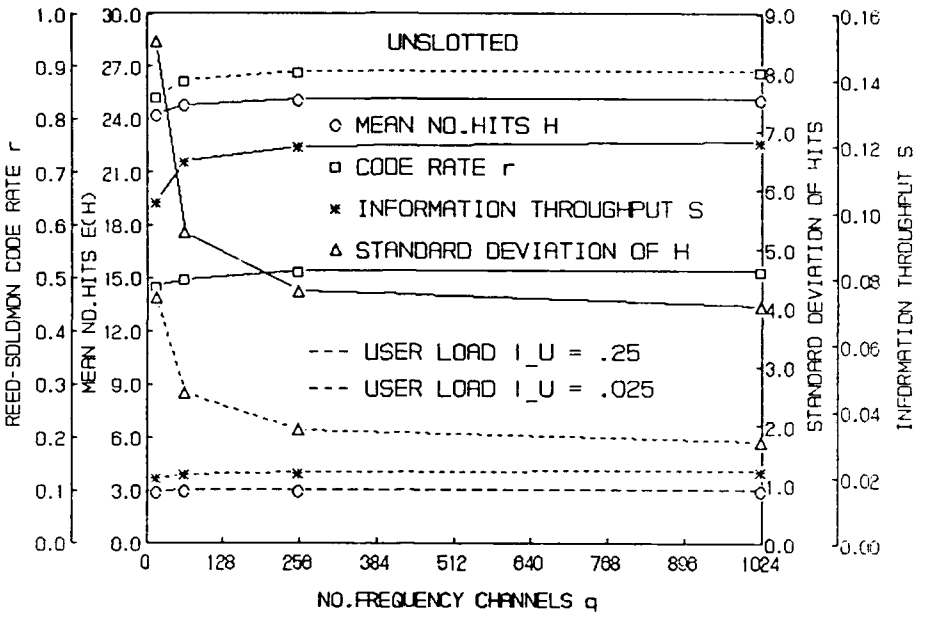

Figure 2.6: E(H), StdDev(H), S, and optimal code rate k/L versus spread factor q

mean number of hits will be able to correct almost all packets.

Figure 2.6 shows the performance as a function of q for $\ell_U = .25$ and for $\ell_U = .025$, where unslotted operation is used and $L = 64$. The mean and standard deviation of the number of hits per packet, the optimal coding rate k/L, and the corresponding information throughput S are all shown versus q. Generally, performance is relatively flat except for the standard deviation, which decreases quickly to its limit $\sqrt{Le^{-2\ell_U}(1 - e^{-2\ell_U})}$ as q is increased. A fairly substantial gain in information throughput is apparent for the $\ell_U = .25$ case as q is increased from 16 to 64. This is due to the much smaller standard deviation, allowing for more efficient coding.

Figure 2.7 illustrates the effect of user traffic burstiness (δ) and overlap tolerance (γ) on performance. Figure 2.7 shows that there is a small loss in throughput if the user traffic is bursty. This is an important aspect of spread spectrum systems: it makes little difference in performance as to whether the traffic is bursty or not. Figure 2.7 also shows that the value of ℓ_U that maximizes S depends on γ; this type of behavior was also found in [57].

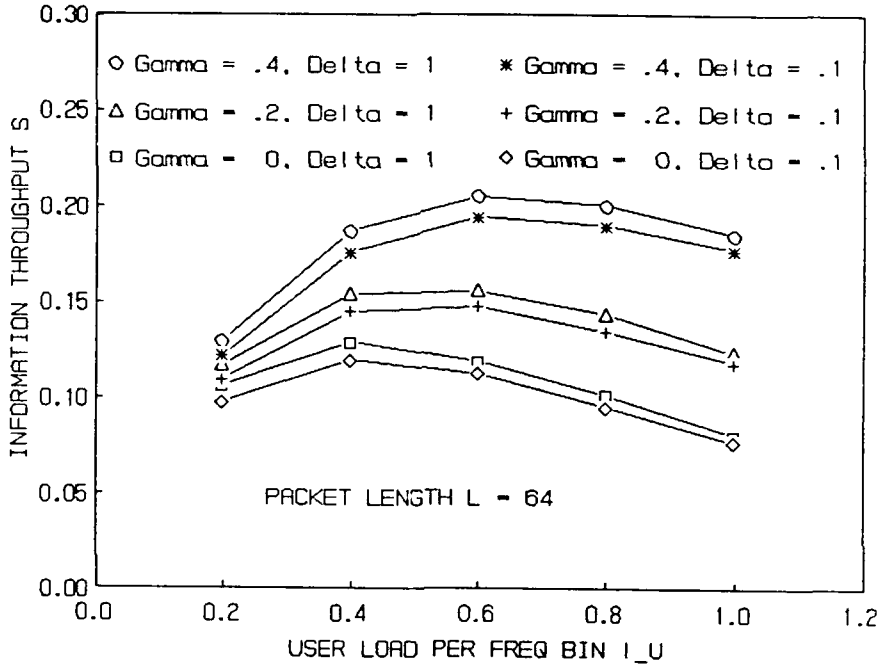

Figure 2.7: S versus ℓ_U for various tolerances γ and bursty ($\delta = .1$) or continuous ($\delta = 1$) traffic

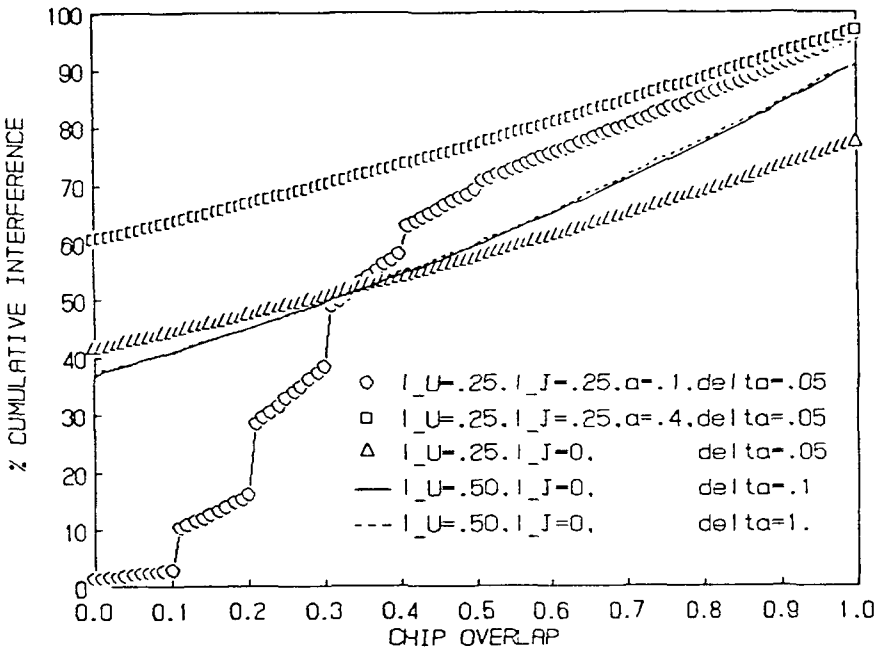

Figure 2.8: Symbol interference probability distributions

2.4.2 Jamming environment.

We now present simulation results for a jamming environment. First consider the interference suffered by a typical single symbol. Figure 2.8 illustrates the probability distribution for the symbol interference for several cases in which the total load per frequency bin $\ell_U + \ell_J$ is fixed at 1/2. The case $\ell_U = \ell_J = 1/4$ is shown for jam pulse lengths of $a = .1$ and $a = 4$ (measured in symbol times), where the user traffic is bursty. The effect of the short pulse ($a = .1$) is clearly evident, and can have a significant impact on the symbol erasure probability depending on the value of γ. Also shown is the case where $\ell_U = .5$ and $\ell_J = 0$ (no jamming), so that a comparison can be made regarding the difference between symbol-level interference caused by other users or caused by jamming. Finally, the case $\ell_U = .5$ and $\ell_J = 0$ is shown for continuous user transmissions ($\delta = 1$), for comparison against the bursty case.

The remaining figures illustrate performance at the packet level. Figure 2.9 shows the

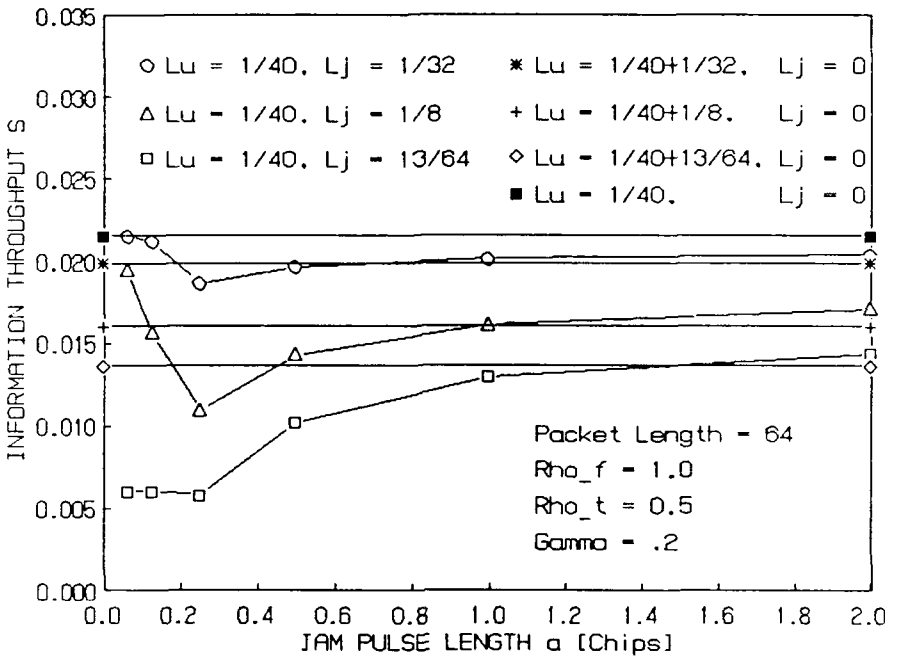

Figure 2.9: Throughput S versus jam pulse length a, user load $\ell_U = .025$, various jammer loads ℓ_J

effect of the jam pulse length a on throughput when $\ell_U = .025$ and $\gamma = .2$. A full-band jammer is assumed, with $\rho_t = 1/32$, $\rho_t = 1/8$, or $\rho_t = 13/64 = .203$. The pulse length that degrades the throughput the most occurs where a is approximately equal to γ. If $\ell_J < \gamma$ and the pulse length is made smaller than γ then the effect of the jammer diminishes (throughput increases). However, if $\ell_J > \gamma$ (i.e., the case where $\ell_J = 13/64$), then the degradation remains effective even for $a < \gamma$. This is because as $a \to 0$ with fixed ℓ_J, every symbol is hit with very close to $\tau_J = \ell_J$ interference.

Also shown in Figure 2.9 are results for comparing the relative degradation between jamming and multiuser interference. One can conceptualize a group of users in two scenarios: one in which there is a jammer of load ℓ_J, and the other in which there is no jammer but additional bursty users that add a load of ℓ_J. This latter scenario is modeled using $\ell'_U = .025 + 1/32$, $\ell'_U = .025 + 1/8$ and $\ell'_U = .025 + 13/64$ with $\ell'_J = 0$. The resulting information throughput was scaled by the factor $\ell_U/(\ell_U + \ell_J)$ so that a fair comparison can be made to the jammed cases. The resulting information throughput values appear as horizontal lines (they do not depend on a). From Figure 2.9 we see that if the jam pulse length a is small enough (but not below γ unless $\ell_U > \gamma$), then the jamming interference is worse than an equivalent amount of user interference. However, if a is large (a few symbol lengths) then the multiuser interference is slightly worse than the corresponding jammer interference would be.

Figure 2.10 considers the effect of varying ρ_f and ρ_t when $\ell_J = \rho_f \rho_t = 1/2$, i.e., the jammer intensity is fixed. The jam pulse length is held constant at $a = 1$, and many bursty users can transmit. We see that the performance is not highly dependent on the selection of ρ_f (for fixed ℓ_J), and furthermore the performance appears to be monotonic, i.e., the maximum degradation occurs at the boundary point $\rho_f = \ell_J$ and $\rho_t = 1$.

2.5 Conclusions

A model has been defined for a spread spectrum system, and performance has been derived for the aspects of system variables by both mathematical analysis and simulation. Interference has been characterized at both the symbol level and the packet level. Values for the jamming parameters a, ρ_t and ρ_f that cause maximum degradation in the users' throughput were determined. A number of specific examples were presented to illustrate the results.

The following conclusions can be made:

1. As the number of frequency bins q increases, the difference in performance between slotted and unslotted operation becomes insignificant.

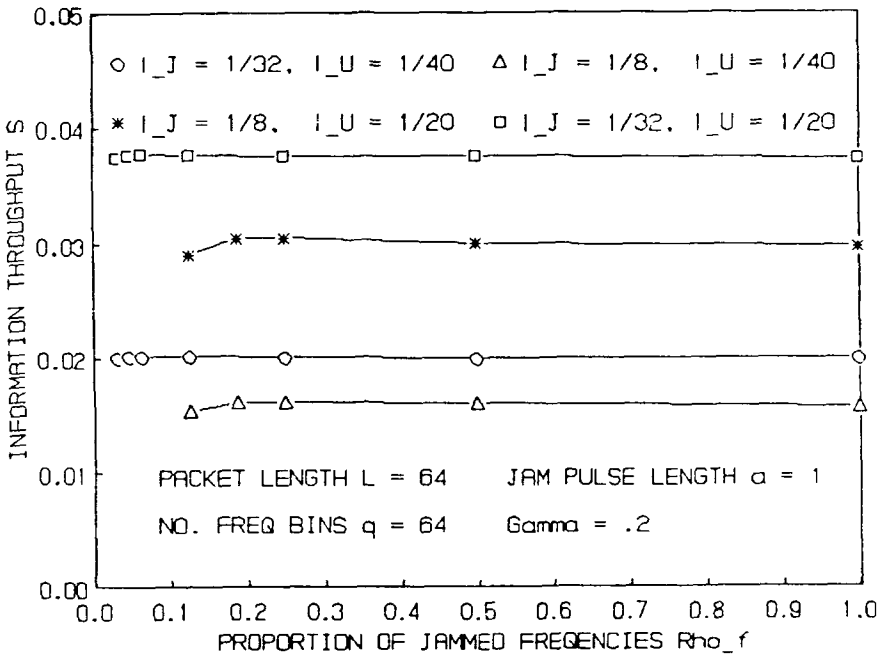

Figure 2.10: Throughput S versus proportion of frequencies jammed ρ_f, multiple bursty users

2. For large q, only slightly less throughput is obtainable when the traffic is bursty as compared to continuous transmission by the users. This fact justifies the consideration of random access techniques in a spread spectrum environment.

3. The effect of the jamming pulse length a is closely related to γ, the amount of interference that a symbol can tolerate. If the jamming pulse length is large, the effect of the jammer is similar to additional user traffic of an equal load.

4. Although there is significant performance variation in a single jammed user depending on how time and frequency are jammed, there is no such strong dependence in the multiuser environment.

Chapter 3

A Performance Comparison of Control Policies

Abstract

A performance analysis of slotted ALOHA with frequency-hopped code division multiple access is presented, with emphasis on the effects of the retransmission control policy. Static and dynamic control policies are considered. Performance using static control is shown to be highly sensitive to the relationship between the packet generation process and the chosen retransmission probability. Dynamic control, on the other hand, is very robust in that it provides high throughput over wide ranges of arrival rates. Delays are generally quite small when system parameters are properly set. A simple rule for computing the retransmission probability as a function of the backlog is provided and is very close to the analytically derived optimal value. Numerical performance evaluation is given for the case of a network of 250 users and a spread factor (number of hopping positions) of 100 and where the other system parameters are varied; numerous graphs illustrate the key concepts. Conclusions and suggested extensions of the work are given.

3.1 Introduction

Use of an appropriate control policy is central to achieving stable operation in any ALOHA system. In this chapter, we present investigations of control policies for slotted ALOHA random access in a frequency-hopped code division multiple access (FH-ALOHA) environment. The control policy is defined by the form of the retransmission probability β. Two cases are

considered: static control, where β is a constant; and dynamic control, where β is a function of the current number of nodes that have packets to transmit. The analysis presented permits a direct comparison of the performance of these two classes of control. It is shown that static control can achieve approximately the same performance as dynamic control for a conditionally binomial (finite source) arrival process provided the packet arrival rate is fixed and known and provided the retransmission rate is tuned properly. However, the static control scheme requires rigorous matching between the arrival process and retransmission rate, with even small deviations from the optimal resulting in poor performance (a similar but less pronounced sensitivity is shown to exist for the code rate). Dynamic control, on the other hand, is very robust in that it provides high throughput over wide ranges of arrival rates. Thus, dynamic control yields major performance gains over static control for networks where a priori information regarding traffic statistics is lacking or where traffic loads are subject to large variation, as is typical in tactical military communications networks.

The FH–ALOHA system is analyzed by modeling the underlying Markov chain; this type of approach was used by Raychaudhuri [9] in the static controlled CDMA setting. The mean drift associated with the Markov chain is often used to measure stability, with unstable systems typically characterized by multiple zero crossings ("bistability"). It is shown that the form of the drift can be very sensitive to the arrival process, and to a lesser extent, to the chosen code rate.

There are several types of dynamic control procedures for slotted ALOHA systems. In this chapter, we focus on backlog-based retransmission schemes. Hajek [39] investigated such a scheme in the FH slotted ALOHA context that is stable in the sense that the system state process is ergodic when the arrival process is independent of the system state (the so-called infinite population model). Additional stability results were presented for CDMA–ALOHA channels by Ghez et al. [62]; a discussion of their work is given in Section 3.3.

We assume the network consists of a finite number of users that are symmetric in terms of their traffic statistics as well as the manner in which they access the channel. The network is fully connected (single-hop), and only interference from other users is considered. Each user is assumed to have at most one packet available for transmission at a time. To simplify the analysis, the dynamic control model used is "genie-aided" in that each user is assumed to have perfect knowledge of the network backlog; in a real system, this would be estimated on the basis of feedback. A simple rule for computing the retransmission probability as a function of the backlog is provided and is very close to the analytically derived optimal value. Numerical performance evaluation is given for the case of a network of 250 users and a spread factor of 100 and where the other system parameters are varied.

The slotted ALOHA frequency hopped multiple access (FHMA) model is given in the next section. The mathematical analysis presented in Section 3.3 provides a derivation of

the backlog control function, and formulas for computing the system state probabilities are derived in Section 3.4. Numerical results are illustrated in Section 3.5, and conclusions and suggested extensions of the work are given in Section 3.6.

3.2 Slotted ALOHA FHMA Model

Frequency hopped multiple access (FHMA). The scheme we are considering uses code division multiple access (CDMA) in which transmitting nodes use different spreading codes in a frequency-hopped system. N users transmit over a common wide frequency band that is divided into q frequency bins (subchannels). Each frequency bin can support narrow band communication. A packet consists of L symbols that are transmitted serially with each symbol on a frequency bin that is chosen according to some pattern. We model the pattern as a memoryless sequence with each frequency chosen uniformly among the q possible bins. We assume that there is no conflict due to multiple transmitters simultaneously sending data to the same receiver or due to half-duplex operation.

Time is slotted, and each transmission must begin on a network synchronization boundary, where the slot time is at least enough to transmit a packet. We assume that network synchronization is not feasible at the symbol level. The hop interval is taken to be equal to the dwell interval, and a single symbol is assumed to be transmitted per hop. If two or more active transmitters choose the same frequency bin during overlapping symbol transmissions, then a "hit" occurs. We assume that if any overlap occurs at all, then the symbol cannot be demodulated correctly. The receiver is assumed to have perfect side information, so that a symbol is either received correctly or is erased. Each packet is a single extended Reed-Solomon (L, k) codeword. Up to $L - k$ symbol erasures can be tolerated in a packet.

Packet arrival process. We assume that traffic is generated as follows. Each node is in one of two states: thinking or backlogged. A node is backlogged if it has a packet to transmit, otherwise it is in the thinking state. A new packet can be generated only while the node is in the thinking state. (This implies that each node can buffer at most one packet.) Conditioned on being in the thinking state, a node generates a new packet for the current slot with probability Δ independent of the other nodes and independent of previous slots. It is possible that a packet is generated immediately following a successful transmission (zero time in the thinking state). Thus, the time until a node generates a new packet is a geometric r.v. with mean $(1 - \Delta)/\Delta$. Traffic is symmetric in that Δ is assumed to be identical across all the nodes (conditioned on being in the thinking state). We denote the number of new packets arriving at time t (aggregated over all nonbacklogged users) by A_t.

Discussion. Numerous authors have used the two-state (thinking or backlogged) user model in studies of slotted ALOHA systems. The "unbuffered" users can have at most one outstanding packet at a time. This model suffers from the presumption that the link layer protocol is free to throttle the higher layer, as though the application will come to a halt (or is interrupted) until the currently backlogged packet is successfully transmitted. (Alternatively, packets generated while the node is backlogged are simply lost.) A seemingly more realistic model would account for queueing of packets, with an arrival process that is independent of the success rate of the channel. If each user offers bursty traffic in the sense that the time spent between generating new packets is much larger than the time required to successfully transmit a packet, then buffering would be rare and the two-state user model is an accurate approximation to the buffered case. However, to approach the capacity of the unspread slotted ALOHA channel (e^{-1}), the number of such bursty users must be large (say $N = 50$ or more).

The analysis based on a two-state user model was extended to the CDMA environment by Raychaudhuri [9]. Unfortunately, extending the above rationale for the model would require that the number of users is scaled in proportion to the spread spectrum processing gain q. For example, if $q = 100$, then we need on the order of 5,000 "bursty" users to load the channel near its capacity. The applicability of such a model is quite limited, although it may be applicable to terrestrial users sharing a satellite with a wide footprint. Such a large population network is not numerically amenable to the analytical approaches used in this report, due to the enormous size of the associated state space.

We will use the two-state user model even though the users are not necessarily bursty, i.e., even though Δ is large. The limiting case where $\Delta = 1$ can be interpreted as follows. First, this could correspond to the case where each node transmits its status (e.g., user location, sensor reading) as often as the channel permits. Alternatively, $\Delta = 1$ (zero time in the thinking state) corresponds to the worst case contention for the channel, since every node always has traffic, and thus places a lower bound on performance that can be used in approximating performance of the buffered case. That is, this corresponds to the heavy traffic case where each node's buffer rarely becomes empty.

It is important to understand the implications of the model assumptions, as will be clear when interpreting derived performance results. For example, it is not necessarily appropriate to think of Δ as a fixed parameter associated with user requirements, since the user's throughput can be significantly less than Δ packets per slot.

In practice, frequency hopping is used primarily for antijam purposes, with CDMA capability being something of a side benefit. In this chapter, we do not investigate the impact of jamming and defer the study of jamming to the following chapter. However, clearly the presence of jamming will reduce the available capacity so that the number of bursty users

supportable will be much less than indicated above. Therefore, the use of a two-state user model may then be easily justified. Also, in an unspread environment a random access protocol like ALOHA is efficient when there are many bursty users, but other schemes such as TDMA or reservation-based protocols are better otherwise. However, our work in chapter 2 (see also [63]) has demonstrated that in a spread spectrum environment the performance is *not* very dependent on the burstiness of the traffic. This implies that consideration of FH-ALOHA with large Δ values is appropriate.

First transmission protocol and backlog definition. When a new packet is generated, it is transmitted according to the first transmission protocol. Two first transmission protocols are considered, the Immediate First Transmission (IFT) protocol and the Delayed First Transmission (DFT) protocol. The IFT protocol dictates that as soon as a new packet arrives, it is transmitted. The DFT protocol has the new packet transmitted with probability β, the same as if it were a retransmission. If a new packet is not transmitted in the first slot or if it is transmitted but fails to be received due to interference from other transmissions, it joins the backlog. The backlog at time t, denoted B_t, is the number of packets that have been in the system at least one slot but have not yet been transmitted successfully. The total number of packets requiring transmission during slot t is $A_t + B_t$.

Given the number of backlogged nodes B_t, the expected number of new packets arriving at time t is $\Lambda = \Lambda(B_t) = (N - B_t)\Delta$. We let X_t denote the number of nodes that transmit during the t^{th} slot. For IFT, X_t consists of all A_t new arrivals plus a number that is binomially distributed with parameters β and B_t. For DFT, X_t is binomially distributed with parameters β and $A_t + B_t$. The backlog process evolves according to

$$B_{t+1} = B_t + A_t - S_t \tag{3.1}$$

where S_t is the number of successfully transmitted packets in slot t.

Retransmission control schemes. Both static (open-loop) control and dynamic (closed-loop) control procedures are considered. A static control procedure simply keeps β (and other parameters such as the code rate) as a constant. Backlogged-based retransmission dynamic control procedures adaptively vary β as a function of the network congestion.

All of the control schemes require some form of positive acknowledgment. We assume for simplicity that acknowledgments are 'free', i.e., cause insignificant interference and delays.

In backlog-based control, the backlog must be estimated by monitoring the shared communications medium. Several techniques have been offered in the literature for forming these estimates (e.g., [39]). In this chapter, we make the simplifying assumption that every node

has perfect knowledge of the current backlog B_t. Clearly, this will result in somewhat optimistic performance characterization. However, experience with unspread slotted ALOHA systems has taught us that very little performance difference occurs between the "genie-aided" model and the realistic models that account for estimated backlogs [27]. In chapter 5, we will show that practicable estimation schemes yield performance that is quite close to the "genie-aided" model.

Although we assume B_t is known, we assume that A_t is not known to the users. Thus in either IFT or DFT operation, the dynamic control function $\beta(B_t)$ must be selected to account for the r.v. A_t. We derive the function β next.

3.3 Dynamic Control Function

Given that B_t is known (or an estimate for it), we still must identify the form of $\beta = \beta(B_t)$. This will depend on whether IFT or DFT is employed: β_{IFT} or β_{DFT}. We choose β so as to maximize the expected number of successes $E(S)$ in the slot. We proceed to derive an expression for $E(S)$ assuming that B and β are given.

3.3.1 The optimal dynamic control function.

$$E(S \mid B) = \sum_x E(S \mid X = x) \sum_{a=0}^{N-B} \cdot P(X = x \mid A = a, B) P(A = a \mid B) \tag{3.2}$$

where

$$P(A = a \mid B) = \binom{N-B}{a} \Delta^a (1-\Delta)^{N-B-a}, \quad 0 \le a \le N-B \tag{3.3}$$

and

$$P(X = x \mid A = a, B) = \binom{B}{x-a} \beta_{\text{IFT}}^{x-a} (1-\beta_{\text{IFT}})^{B-x+a}, \quad a \le x \le a+B \tag{3.4I}$$

if IFT is used, and

$$P(X = x \mid A = a, B) = \binom{a+B}{x} \beta_{\text{DFT}}^{x} (1-\beta_{\text{DFT}})^{a+B-x}, \quad 0 \le x \le a+B \tag{3.4D}$$

if DFT is used. $E(S \mid X)$ remains to be derived. We do so using two approximations. First, we assume that the symbol hit probabilities in the same packet are independent and identical. A justification of this approximation is given in [58, 64]. Second, we assume

that the success probability P_c for each of the X packets transmitted is independent and identical, so that the number of successful packets is binomially distributed with parameters X and P_c. If only two users transmit ($X = 2$) and one fails, then the other certainly must fail, illustrating that some dependence is actually present. However, for moderate to large processing gains q, the assumption of independence is a good approximation.

Since we assume that the network is asynchronous at the symbol (hop) level, and memoryless hopping patterns are used, the probability of a symbol being hit by a single other transmitter is

$$P_h = 2/q - 1/q^2 \tag{3.5}$$

and the probability of being hit by one or more of the other $X - 1$ transmitters is

$$P_{h,X} = 1 - (1 - P_h)^{X-1}. \tag{3.6}$$

The probability of a packet being correctly decoded, given $X - 1$ other transmissions, is (since we can correct up to $L - k$ erasures)

$$P_{c,X} = \sum_{i=0}^{L-k} \binom{L}{i} P_{h,X}{}^i (1 - P_{h,X})^{L-i}. \tag{3.7}$$

Finally, the expected number of successes given X transmissions is

$$E(S \mid X) = X P_{c,X}. \tag{3.8}$$

From (3.2)–(3.8) we can derive the mean number of successes for any given backlog B and retransmission probability β for either the IFT or DFT protocol.

The *optimal dynamic control function* for each case, denoted β^*_{IFT} or β^*_{DFT}, is that value of β that maximizes $E(S \mid B)$ according to the above formulae for each backlog B. We have developed a program that numerically determines the optimal dynamic control function for either IFT or DFT.

3.3.2 A simple, nearly optimal dynamic control function.

Early analyses of the ALOHA protocol presumed that the total channel traffic was a Poisson process with constant parameter G. Throughput was then found to be maximum at some unique value of G, and degradation occurred if G deviated from this value. Gerla and Kleinrock [65] constructed a closed-loop control for unspread slotted ALOHA that attempted to maintain the intensity of the channel traffic close to unity (since $G^* = 1$ is optimal in the unspread slotted ALOHA case). Hajek and van Loon [26] devised a realizable dynamic

control policy that was proved to be stable in the sense of the infinite population model and justified the "local Poisson approximation" for the process of arrivals plus retransmissions.

This concept was extended to FHMA by Hajek [39]. The general "multipacket" channel (of which spread spectrum is a special case) was considered by Ghez et al. [62]. They showed that the supremum throughput for multipacket slotted ALOHA is given by

$$S_{\sup} = \sup_{G \geq 0} \sum_{x=1}^{\infty} E(S \mid X = x) \frac{G^x}{x!} e^{-G}, \tag{3.9}$$

i.e., we may take the channel traffic X to be a Poisson r.v. with parameter G and maximize the throughput with respect to this parameter. The value of G that attains the supremum in (3.9) is denoted G^*. Ghez et al. [62] essentially showed that although β^*_{DFT} is optimal for the "ideal" (genie-aided) multipacket slotted ALOHA DFT system, it is also stable (in the infinite population sense) for any load less than $S_{\sup}$ using the simple rule

$$\beta_{\mathrm{DFT}}(A + B) = G^*/(A + B) \tag{3.10}$$

(their genie is more informative than ours in that $A+B$ is assumed known and not just B). A similar result holds for the IFT case. Finally, they showed that there exist *realizable* control policies that achieve stable performance for loads less than $S_{\sup}$ with something/nothing feedback using a rule

$$\beta(\widehat{A+B}) = G^*/(\widehat{A+B}) \tag{3.11}$$

where $\widehat{A+B}$ is an estimate of $A + B$ that is updated according to

$$\widehat{A+B}_{t+1} = U(\widehat{A+B}_t, F_t)$$

for some function U, where F_t is the feedback (0 or $\bar{0}$) for slot t (see [62], Thm. 4 for details on the form of U).

We use a genie that tells us only B and not $A + B$ so as to more easily treat both the IFT and DFT cases. In either case we wish to drive the system with a constant target load of G^*. In the IFT case, the mean number of transmissions is $E(X \mid B) = \Lambda + \beta B$ where

$$\Lambda = \Lambda(B) = \Delta(N - B) \tag{3.12}$$

is the expected number of arrivals. The corresponding simple rule that causes $E(X \mid B) = G^*$ is therefore

$$\beta_{\mathrm{IFT}}(B) = \min\Big(\frac{[G^* - \Lambda]^+}{B}, 1\Big), \tag{3.13}$$

where we take $\beta_{IFT}(0) = 1$. In the DFT case, $E(X \mid B) = (\Lambda + B)\beta$ so the simple rule is

$$\beta_{\text{DFT}}(B) = \min\Big(\frac{G^*}{\Lambda + B}, 1\Big). \tag{3.14}$$

Numerical results to be shown in Section 3.5 demonstrate that (3.13, 3.14) are in close agreement with the optimal values of β^*_{IFT}, β^*_{DFT} computed via (3.2–3.8).

We note that the feedback assumed in [62] is extremely crude, namely, each user knows only whether or not zero stations transmitted. If q is large, then we expect G^* to be large, and therefore proper control implies that the chance of zero transmissions should be very small. The conclusion made in [62] is that even for this very limited feedback, maximal throughput is attainable. However, they do not consider *delay* performance, and one expects that in such a system the delays could be quite large. In our work, we assume a genie tells all users the backlog value B. We expect that the delay performance with such feedback will be significantly superior to a system with only something/nothing feedback.

While the formulas above are applicable to the general FH–ALOHA system where the code rate k/L is arbitrary, we can specialize them to the situation where the code rate is chosen optimally. We know from Kim and Stark [61] that if the number of transmissions per slot is constant and if q and L are large then the throughput is maximized when the normalized load per frequency bin is $1/2$ and the code rate is $k/L = e^{-1}$; the resulting normalized throughput is $e^{-1}/2$ (the same optimum as unspread unslotted ALOHA). From our earlier work [63] we know that the performance of FH- -ALOHA is not very dependent on the burstiness of the users. Therefore, we expect that approximately the same code rate and load values will optimize the dynamically controlled ALOHA system where the number of users transmitting per slot is essentially Poisson(G). We conclude that we should choose $k/L \approx e^{-1}$ and that

$$G^* \approx \frac{q}{2}. \tag{3.15}$$

In our investigations we took the transmission probabilities to be

$$\beta_{\text{IFT}}(B) = \min\Big(\frac{[G - \Lambda]^+}{B}, 1\Big) \tag{3.16}$$

and

$$\beta_{\text{DFT}}(B) = \min\Big(\frac{G}{\Lambda + B}, 1\Big) \tag{3.17}$$

where we allowed G to be a free design parameter. Although we expected the best performance to occur at $G = G^*$, we wanted to observe the sensitivity with respect to G.

3.4 Markov Chain Analysis

The evolution of the system backlog is given by eqn (3.1). Since A_t and β (if dynamic) depend only upon the backlog at time t, $\{B_t, t \geq 1\}$ forms a discrete time Markov chain on $0, \ldots, N$. Raychaudhuri [9] considered the same Markov chain for the static control case. The chain is characterized by the state transition matrix $P = [p_{ij}]$, where

$$\begin{aligned} p_{ij} &= P\{B_{t+1} = j | B_t = i\} \\ &= \sum_{a=\max(0,j-i)}^{N-i} P(A_t = a | B_t = i) \\ &\quad \cdot \sum_{x=i+a-j}^{i+a} P(X_t = x | B_t = i, A_t = a) \\ &\quad \cdot P(S_t = i + a - j | X_t = x), \end{aligned} \tag{3.18}$$

the conditional distribution of the number of arrivals is given by equation (3.3), and the conditional distribution of the number of transmissions is given either by equation (3.4I) or by (3.4D). Note that in the dynamic control case, the β values must be computed before computing the transition matrix. The conditional distribution of the number of successes given the number of transmissions either can be estimated from the empirical distribution found through simulations, or calculated by approximating with a binomial with parameters X and Bernoulli probability given by (3.7).

As in [9], the Markov chain is irreducible, aperiodic, and positive recurrent unless $P_{c,X} = 1$ for $X = 1, \ldots, N$. The stationary probability mass function for the chain can be solved using standard techniques such as power methods or SOR (Successive Over-Relaxation.)

Once the stationary probability mass function (p.m.f.) of the backlog is known, the steady-state composite arrival distribution and the steady-state throughput can be determined. The steady-state composite arrival distribution is the weighted sum of the arrival distributions conditioned upon the backlog, weighted by the steady-state p.m.f. of the backlog.

Since no packets are lost, the steady-state throughput $E[S]$ is equal to the arrival rate $E[A] = \Delta(N - E[B])$ (see (3.12)), where $E[B]$ is the mean backlog. Adjusting for the code rate as well as the number of frequency bins, the information throughput is given by

$$s = E(S) \cdot (k/L)/q. \tag{3.19}$$

The mean number in the system is given by $E[A + B] = \Delta \cdot N + (1 - \Delta)E[B]$, and by Little's result the mean delay $E[D]$ is given by $E[D] = E[A + B]/E[A]$. The mean drift is

the expected one-step change in the backlog and is given by

$$d(i) = \sum_{j=0}^{N} p_{ij}(j - i). \tag{3.20}$$

The mean drift is useful in determining the system stability (see the discussion below).

3.5 Numerical Results

All of the results presented in this section correspond to the specific case of $N = 250$ users, $q = 100$ frequency bins, a packet length of $L = 64$, and use of DFT. Other parameters are varied.

Figure 3.1 illustrates the potential sensitivity of the Markov chain drift function for statically controlled systems. The solid curve in the figure corresponds to the drift for fixed $\beta = .3$, probability of packet generation in thinking state $\Delta = .25$, and use of $k = 22$ information symbols of the 64 comprising the packet (codeword). This case yields a normalized information throughput of $s = .1278$ and a mean packet delay of $E[D] = 3.72$ slots. The dashed curve corresponds to similar parameters except Δ is increased to .28; this causes instability (bistability) to occur. The dotted curve illustrates that a similar instability results if the code rate is increased to 23/64, i.e., an increase of 4.5%. Not all statically controlled cases are necessarily this sensitive. In general, the shape of the drift tends to be more linear as Δ is increased. When the optimum dynamic control function was used, the drift was very nearly linear in all cases we tested.

We note that in the $\beta = .3$, $\Delta = .25$, $k = 22$ case indicated above, the mean time to generate a new packet $(1 - \Delta)/\Delta = 3$, which is close to the mean delay. That is, this case does not correspond to very "bursty" users, and the users are significantly throttled by the channel. The normalized throughput of .1278 implies that the system is nearly optimal, since the largest throughputs we have found with $N = 250$, $q = 100$ are approximately .13. The mean backlog was found to be $E[B] = 101.26$, a rather significant proportion of the total population ($N = 250$). However, this relatively congested appearance (being close to the capacity$\approx$.13 and having such a large proportion of the population backlogged) does not cause excessive delays. This pleasant aspect of small delays in FH-ALOHA systems has been previously noted [9, 39].

We next investigate the sensitivity of statically controlled FH-ALOHA with respect to the arrival rate per user while in the thinking state. Since the time until a user generates a new packet in the thinking state is geometric with mean $(1 - \Delta)/\Delta$ [slots], we define the

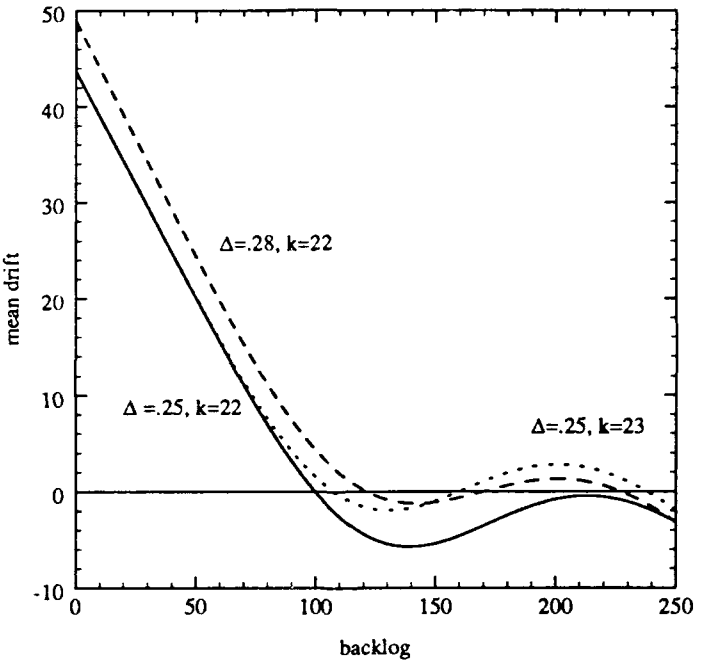

Figure 3.1: Throughput vs. arrival rate, dynamic & various static β's and code rates

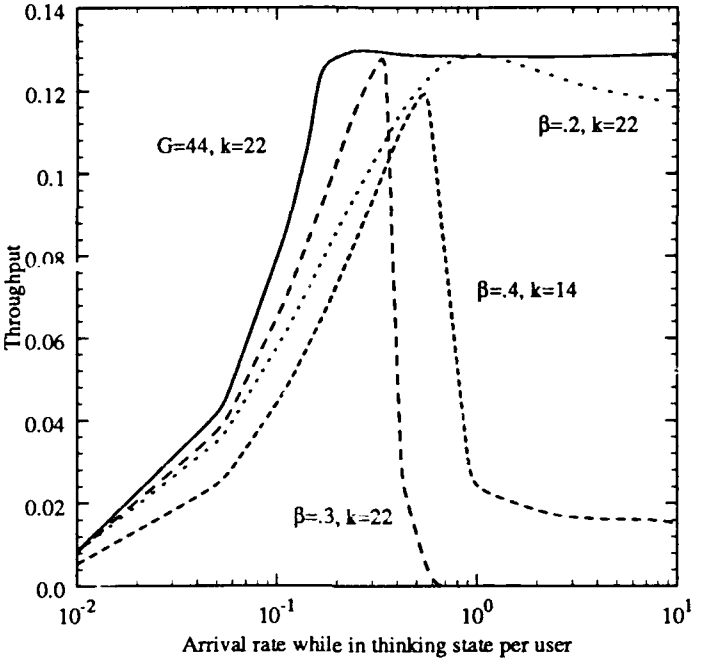

Figure 3.2: Throughput vs. arrival rate, dynamic & various static β's and code rates

arrival rate to be $\eta = \Delta/(1-\Delta)$. Figure 3.2 presents the normalized throughput s versus the arrival rate η for three static control examples ($\beta = .4$, $k = 23$; $\beta = .3$, $k = 21$; and $\beta = .2$, $k = 19$) and a dynamically controlled case where $G = 50$ (see (17) and $k = 22$. The code rates for the statically controlled cases were chosen so as to maximize the peaks of each of the curves. The case $\beta = .3, k = 22$, and $\eta = 1/3$ ($\Delta = .25$) of Figure 3.1 is included in Figure 3.2. It is seen that if the arrival rate is slightly larger then the throughput falls dramatically, and substantial degradation is also present if the arrival rate is smaller than 1/3. This illustrates that precise a priori knowledge of the arrival statistics is needed in order to approach theoretical capacities. On the other hand, the throughput of the dynamically controlled case is seen to be essentially independent of the arrival rate, once there is sufficient traffic to fully utilize the system.

Figure 3.3 also considers the throughput performance for the static controlled cases $\beta = .2$, $\beta = .3$ and $\beta = .4$ as well as the $G = 50$ dynamically controlled case. However, in this figure, the arrival rate is held constant at $\eta = .25$ ($\Delta = .2$) and the effect of varying the code rate is studied. Again, we see that precise congruence between the code rate and arrival rate

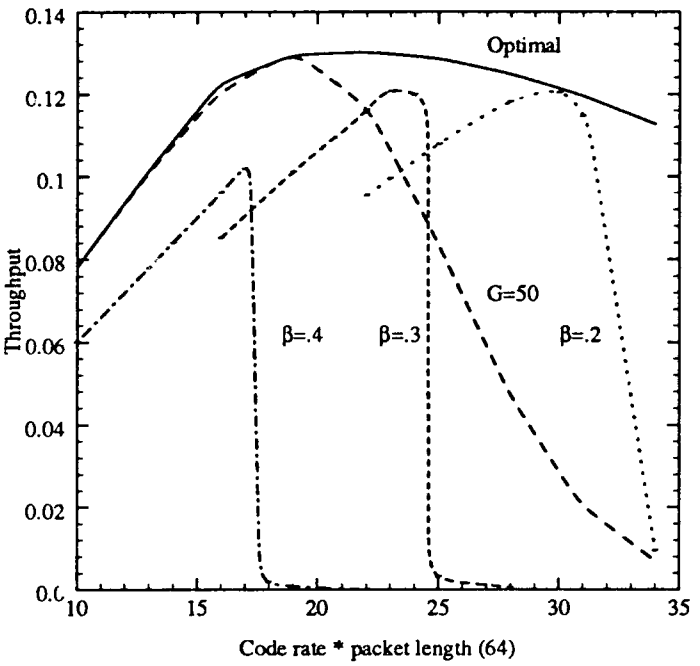

Figure 3.3: Throughput vs. code rate, dynamic & various static β's, arr. rate =.25 (Δ=.2)

is needed to achieve good performance for the statically controlled cases, but much greater tolerance is available with dynamic control. Also shown in the figure is the throughput that would be obtained if the optimal dynamic control function is used.

Figure 3.4 illustrates the sensitivity of throughput to choice of code rate for various static control schemes as well as the dynamic control scheme with $G = 50 = q/2$. For each curve, the optimal code rate (in the sense of maximizing throughput) is plotted versus the arrival rate. We see that the optimal code rate is highly dependent on the arrival rate for all static control cases, but very little dependence is present for the dynamic control case. This clearly illustrates the robust nature of dynamic control in stark contrast to static control.

Next, suppose that we can accurately predict the arrival rates, and therefore can always choose the best code rate. Figure 3.5 compares the throughput versus arrival rate for various static control schemes and the optimal dynamic control scheme when the optimal code rate is used in all cases. We see that under these assumptions there are static control schemes that can achieve performance similar to the dynamic control scheme. The important conclusion to make is that dynamic control does *not* necessarily yield substantially better throughput

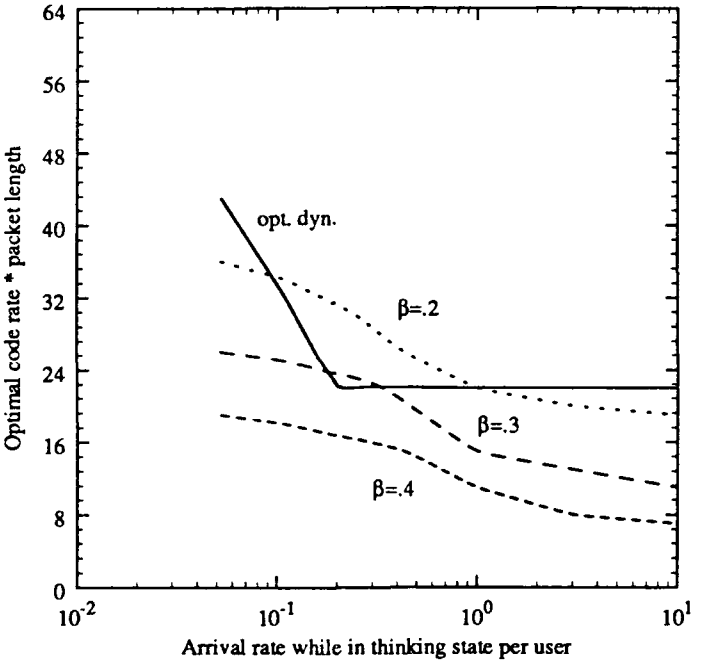

Figure 3.4: Optimal code rate vs. arrival rate, various control schemes

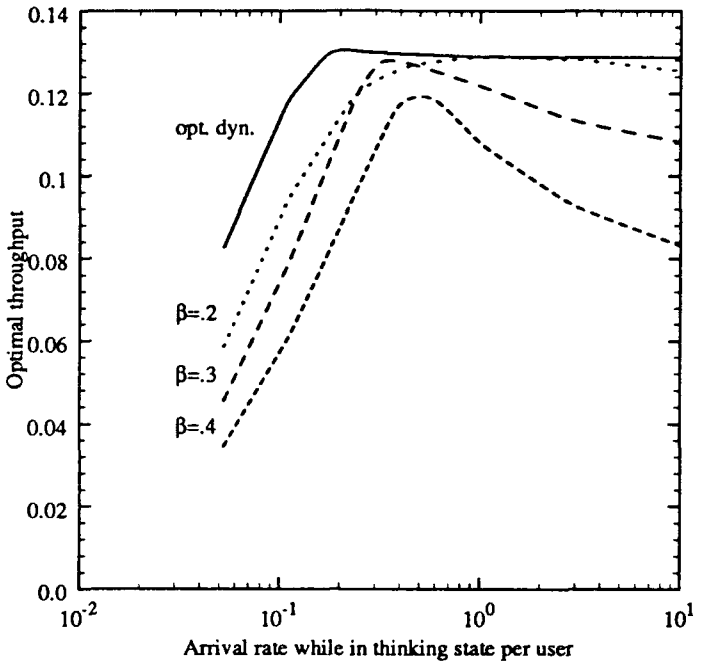

Figure 3.5: Optimal throughput vs. arrival rate, various control schemes

than static control *if the arrival rates are known precisely.* The "stability" or "robustness" provided by dynamic control procedures is with respect to the degree that a priori knowledge is required to fine tune the system design parameters.

Figure 3.6 presents the mean packet delay versus throughput for the same selected cases used in Figure 3.2. We see that generally the mean delays are quite small. For the static controlled cases, the mean delay is approximately $1/\beta$ slots until the maximum throughput is reached. The dynamic controlled case mean delay remains less than 1.5 slots until its maximum throughput is reached.

Of interest is a comparison of the rate of transmissions $E(X)$ for the different control schemes. Figure 3.7 shows the transmission rate versus arrival rate for the same control schemes, again with the code rate optimized at each arrival rate. With sufficient traffic, the dynamic control scheme successfully holds the transmission rate at $G = 50$.

Figure 3.8 investigates the sensitivity of the performance of dynamic control to the choice of transmission factor, G. Illustrated is the throughput for various G values ($G = 25, 50$, and 75). The solid curves correspond to the cases where the optimal code rate is used throughout,

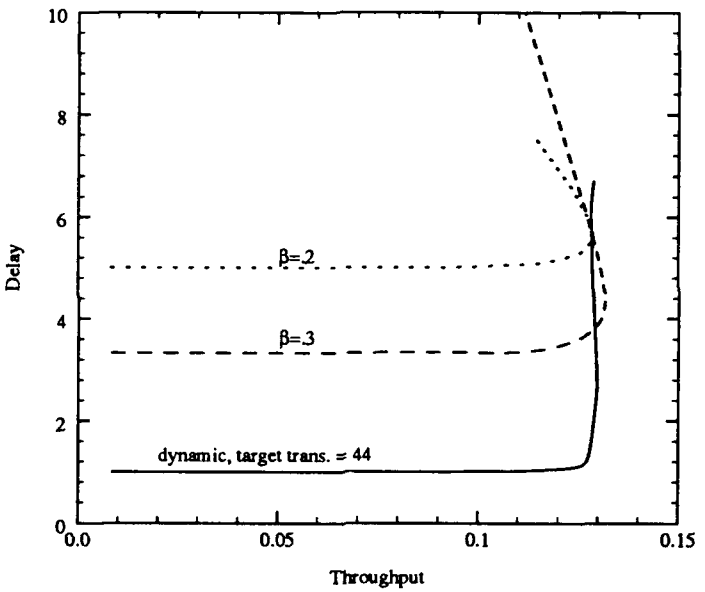

Figure 3.6: Comparative Delay Performance

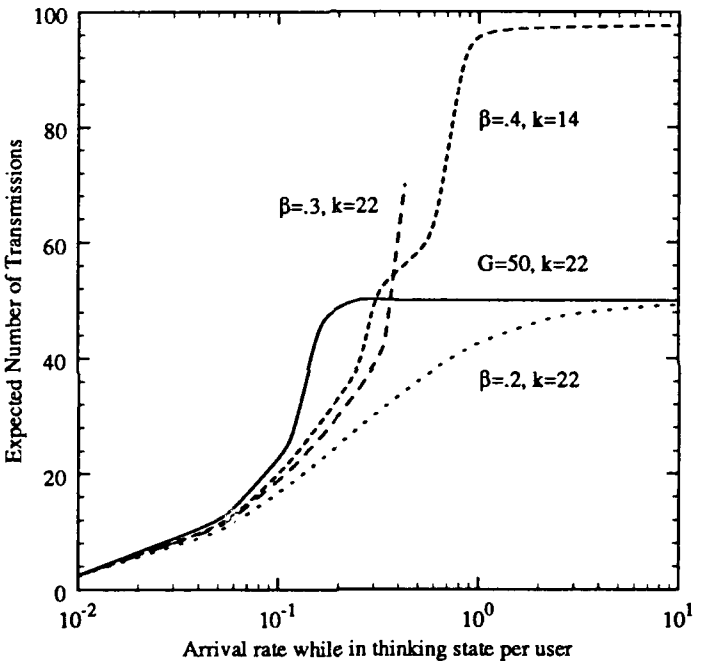

Figure 3.7: Expected Number of Transmissions vs. Arrival Rate

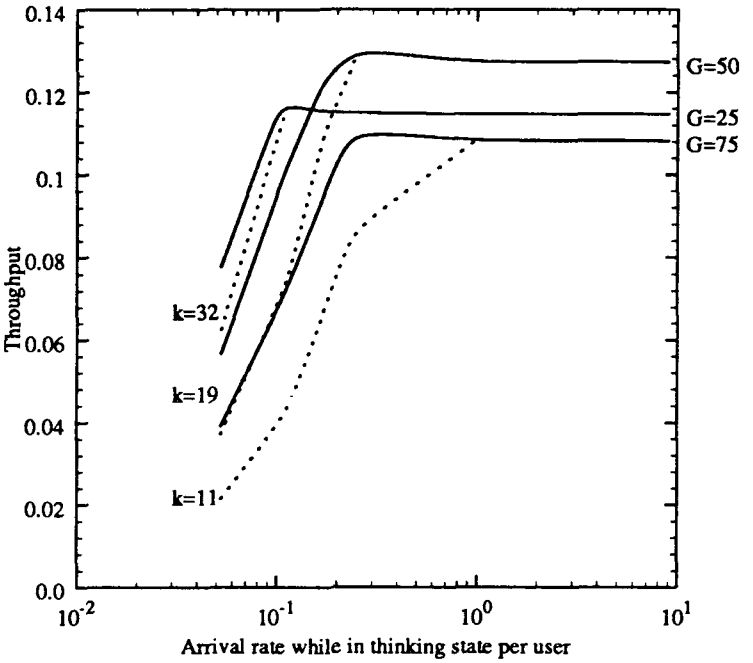

Figure 3.8: Sensitivity of Dynamic Control Transmission Factor

whereas the dotted curves correspond to the throughput achieved if the code rate is held fixed at the optimal value for high arrival rates.

3.6 Conclusions

A performance comparison of static and dynamic control policies for slotted ALOHA systems using frequency hopped multiple access has been presented. Evaluation of throughput and delay was derived through both mathematical analysis and simulation. A simple dynamic control function of the network backlog was developed.

Numerical examples illustrated the robustness gained through the use of dynamic control policies. Static control policies have been shown to achieve essentially equivalent performance as dynamic control schemes *provided that precise a priori knowledge of the traffic statistics is known*. However, substantial degradation in performance occurs in the statically controlled system if the arrival process deviates from the presumed values used for tuning the system

design parameters. No such sensitivity is present for the dynamic controlled case.

Many directions for extending the work are evident such as the impact of jamming, the incorporation of buffering capabilities, the use of dynamic control policies other than backlogged-based, and the inclusion of acknowledgment traffic. Other areas of research include realizable implementations for sensing channel activity, comparison with direct sequence or hybrid spread spectrum techniques, and analysis of unslotted systems. In the next chapter, we describe our work on the effects of jamming on control policies.

Chapter 4

The Effects of Jamming on Control Policies

Abstract

A performance analysis of the effects of interference due to jamming on transmission control policies for slotted ALOHA with frequency-hopped code division multiple access is presented. Both static and dynamic control schemes are considered. With static control, the transmission probability is fixed, while dynamic control adaptively varies the transmission probabilities as a function of the network backlog as well as the interference level due to jamming. Dynamic control is shown to provide considerable performance improvement over static control when the interference level is unknown or time-varying. Performance is evaluated using both analytical and simulation models. Numerical performance evaluation is given for a network of 250 users and a spread factor (number of hopping positions) of 100 and where the other system parameters are varied.

4.1 Introduction

Random access used in conjunction with spread spectrum can provide efficient and robust communications capability. However, the performance and stability is highly dependent on the interference, traffic load dynamics, and the control policy employed. In this chapter, we present investigations of the effect of interference due to jamming on control policies for slotted ALOHA random access in a fully connected frequency-hopped code division multiple access (FH–ALOHA) environment. The control policy is defined by the form of the trans-

mission probability β. Two cases are considered: static control, where β is a constant; and dynamic control, where β is a function of the backlog (the current number of nodes that have packets to transmit) as well as the interference level. Performance is evaluated using both analytical and simulation models. Static control is shown to achieve approximately the same performance as dynamic control provided the interference level is fixed and known and provided the transmission rate β and code rate are tuned properly. However, the static control scheme requires rigorous matching between the interference level and transmission rate, with even small deviations from the optimal resulting in poor performance. Dynamic control, on the other hand, is very robust in that it provides high throughput over wide ranges of interference levels. Thus, dynamic control can yield major performance gains over static control for networks where a priori information regarding interference is lacking or where the interference is time varying.

Extensive literature in the area of spread spectrum systems and their performance in the presence of interference exists, although most of this work is directed at a single transmitter-receiver pair. The capability of multiple simultaneous transmissions (Code Division Multiple Access, CDMA) has been investigated in numerous papers. For example, Geraniotis and Pursley [66] analyzed frequency-hopped multiple access (FHMA) with fading; and Kim and Stark [61] found optimal code rates for FHMA systems (both papers assume a constant number of continuously transmitting users).

A number of papers describe investigations of random access in conjunction with CDMA but do not explicitly model the backlog process; i.e., the users transmit at random times, but these times are not modeled to account for the dependence on the success of previous transmissions. These papers include Pursley [60], Musser and Daigle [10], Joseph and Raychaudhuri [30], Kim [67], and Clare and Sastry [63]; the latter investigated FHMA performance in the presence of jamming. Analyses of CDMA random access systems based upon static control that account for the backlog process include Raychaudhuri [9], Sastry [59], Ghez et al. [62], and Clare et al. [68]. Dynamic control FH–ALOHA was investigated by Hajek [39]. Dynamic control performance for the general multipacket channel is studied by Ghez et al. [62]. In chapter 3 (see also Clare et al. [68]) we compared performance of static and dynamic control policies for FH–ALOHA. A tree random access scheme for FHMA was analyzed by Geraniotis and Mani [40]. Very little work in the literature considers the impact of jamming interference on the static and dynamic control procedures for spread spectrum–ALOHA protocols.

The work most relevant to this chapter is that of Pronios [56], which investigates the impact of jamming on the performance of slotted ALOHA in combination with either frequency-hopped or direct sequence spread spectrum. Actions that could be taken by the (hostile) jammer to minimize throughput are determined, along with appropriate countermeasures

that the users could take. Pronios [56] considered static transmission control procedures. In our work, we treat both static and dynamic transmission control.

The FH-ALOHA model and analytical approach used in this paper is the same as that used in chapter 3 and [68]. Unlike chapter 3, the emphasis in this chapter is on the effects of jamming interference on system performance.

As in chapter 3, we assume the network consists of a finite number of users that are symmetric in terms of their traffic statistics as well as the manner in which they access the channel. The network is fully connected (single-hop), and interference affects all users identically. The channel model employed is identical to that of [61, 60], except that some number J of the frequency bins are blocked due to interference. Each user is assumed to have at most one packet available for transmission at a time. To simplify the analysis, the dynamic control model used is "genie-aided" in that each user is assumed to have perfect knowledge of the network backlog and the interference level; in a real system, this would be estimated on the basis of feedback. Numerical performance evaluation is given for the case of a network of 250 users and a spread factor of 100 and where the other system parameters are varied.

The slotted ALOHA frequency hopped multiple access model is given in the next section. Numerical results are illustrated in Section 4.3, and conclusions are given in Section 4.4.

4.2 Slotted ALOHA FHMA Model

The model used in this chapter is identical to that used in the previous chapter, with the addition of a model of external interference due to jamming.

External interference. The external interference is modeled as an integer number J of the frequency bins as being "blocked," so that a symbol transmitted in such a bin is surely hit. (Additional interference models have been treated by Pronios [56]; we have not included those models.) Dynamic control procedures under study require that the users are able to determine the value of J ($0 \leq J \leq q$) accurately. J may be time-varying but at a rate that is slow enough to allow the dynamic control mechanism to track the interference level. For example, the users may set aside certain slots where none transmit, so that only the interference is present and J can be determined. We will not pursue specific techniques to implement the estimation of J, but assume that a "genie" tells the users of J.

Retransmission control schemes. Both static (open-loop) control and dynamic (closed-loop) control procedures are considered. A static control procedure simply keeps β as a

constant. Dynamic control procedures adaptively vary β as a function of the network backlog and the level of external interference.

All of the control schemes require some form of positive acknowledgment. We assume that acknowledgments are "free"; the acknowledgment traffic load can be made relatively insignificant through mechanisms that make efficient use of slots for transmitting acknowledgments (e.g., minislots and piggybacking).

In backlog-based control, the backlog must be estimated by monitoring the shared communications medium. Some authors have suggested techniques for deriving estimates of the number of packets transmitted (X_t) during a slot [39, 40, 69]. Procedures for forming a combined estimate for both the backlog and the external interference level is an open problem. As in the case of the estimate for J, we make the simplifying assumption that every node has perfect knowledge of the current backlog B_t. Clearly, this will result in somewhat optimistic performance characterization. However, experience with unspread slotted ALOHA systems has taught us that very little performance difference occurs between the "genie-aided" model and the realistic models that account for estimated backlogs [27], and we intuitively expect the same to hold when spread spectrum is employed.

Although we assume B_t is known, we assume that A_t is not known to the users. Thus the dynamic control function $\beta(B_t)$ must be selected to account for the r.v. A_t. We choose β so as to maximize the expected number of successes $E(S)$ in the slot, as indicated below.

The optimal dynamic control function. The optimal dynamic control function is the same as that given in the previous chapter in equations 3.2–3.8, except that equation 3.6 is replaced by the following equation.

The probability of being hit by one or more of the other $X-1$ transmitters or being hit due to selecting one of the J jammed bins is

$$P_{h,X} = 1 - (1 - P_h)^{X-1}(1 - J/q). \tag{4.1}$$

From (3.2–3.8, and 4.1) we can derive the mean number of successes for any given backlog B and retransmission probability β.

The *optimal dynamic control function* for each case, denoted β^*, is that value of β that maximizes $E(S \mid B)$ according to the above formulae for each backlog B.

The performance analysis of the jammed system was conducted by modifying the models described in chapter 3 to include the additional jamming terms.

4.3 Numerical Results

Performance of the FH-ALOHA system described in the preceding sections has been evaluated using both mathematical analyses and simulation. The analytical model provides essentially exact results and can be used to validate the simulation model, but typically requires more computer time. The simulation is easier to extend (e.g., buffering, non-genie-aided operation, and acknowledgments). In practice, the simulation is used to quickly identify regions of interest, and then the analytical model is used to compute exact values.

All of the results presented in this section correspond to the specific case of $N = 250$ users, $q = 100$ frequency bins, and a packet length of $L = 64$. Other parameters are varied.

The first six figures of this section reflect conditional performance, where the number of users with packets is assumed to be fixed. This allows the effects of the interference and the network congestion on the control policies to be separated from each other. However, only partial performance characterization is obtained, and it can be viewed as the expected behavior for a single slot. Figures 4.7 and 4.8 reflect complete performance characterization, since they show steady state results as derived from the stochastic process (Markov chain) that describes the system operation.

Figures 4.1 and 4.2 investigate the sensitivity of performance with respect to the code rate and the choice of transmission probability β. Both of these may be selected by the design engineer to meet the anticipated system conditions, in particular, the level of interference. However, in practice, the interference level will not be completely known and is likely to change with time. It is of interest to determine performance when the interference deviates from the anticipated level, and to identify techniques to mitigate the degradation. We assume that the transmission probability β may be easily adapted as a function of current conditions, whereas the coding procedure must remain fixed due to implementation simplicity/feasibility.

Figure 4.1 presents the normalized information throughput that is expected in a single slot when the number of users with packets to transmit is 250 and when there is no interference. That is, the ordinate axis corresponds to $E(S|C = 250) \cdot (k/L)/q$. The conditional throughput is plotted versus the number of information symbols k per R-S codeword. Results are given for transmission probabilities $\beta = .1, .2, .3, .4$, and $.5$. Also, the envelope of points corresponding to the maximum conditional throughput is presented. This envelope corresponds to the throughput obtained if dynamic control is employed, so that the optimum β is used. If the number of users that transmitted were a constant 250 every slot, then the optimum design parameters would be $k = 22$ and $\beta = .16856$, resulting in a throughput of $s = .12707$. However, in a random access system in which the users have bursty traffic, the backlog will vary and the best choice of k and β is not as obvious.

When jamming is added, the curves of Figure 4.1 are lowered, and the optimal choice

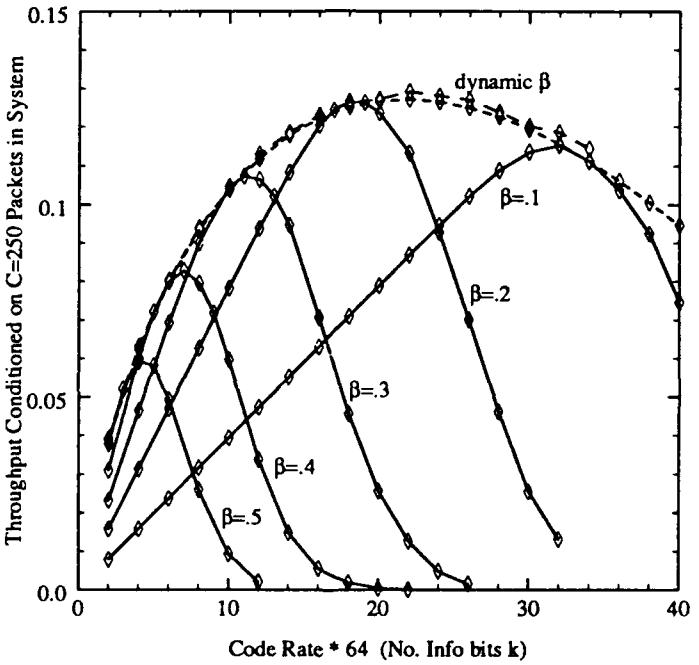

Figure 4.1: Normalized information throughput in one slot when number of stations with packets = 250 versus coding parameter k, no jamming, various β.

of coding parameter k changes, and if static control is used, the optimal choice of β also changes. For example, if it was known that $J = 40$ and that $C = 250$ users had packets, then the optimal design parameters for static control would be $k = 13$ and $\beta = .16978$, resulting in a throughput of $s = .07198$. However, if the system is designed for these conditions but the interference is removed, the throughput increases only to $s = .0877$, which is far short of the value $s = .127$ achievable with $k = 22$ and $\beta = .16856$. Thus the potential improvement by use of adaptive techniques is clear.

Figure 4.2 presents the conditional throughput versus coding parameter k for various interference levels J. Only the cases of β fixed at .2 and dynamic control (β optimized for each code rate and interference level) are shown. This figure illustrates the sensitivity of the control policy to variations in the interference level. For example, if the system is designed for a nominal interference level of $J = 20$, then the static ($\beta = .2$) case is optimized with $k = 15$, yielding $s = .099$. If the interference level is $J = 0$, then s increases to .116, which is 91.7% of the value obtained if $k = 18$ had been used with $\beta = .2$. If the interference is $J = 40$, then the throughput with $k = 15$ and $\beta = .2$ decreases to .051, which is 28.6% less than the value obtained if $k = 10$ had been used. On the other hand, suppose that dynamic control is used in which the interference level can be sensed and β (but not k) can be adjusted accordingly. Again designing for a nominal $J = 20$ interference level, $k = 18$ is optimal. If then $J = 0$, the throughput increases to $s = .124$, which is only 2.6% less than if $k = 22$ had been used. Also, if $J = 40$, then throughput decreases to $s = .069$, which is only 5% less than if $k = 11$ had been used. Therefore, the ability to sense the interference level and adjust β provides robust performance that is nearly as good as if both the code rate and β were allowed to be chosen dynamically.

Figure 4.3 further elaborates on the dependence between the transmission probability β and the interference level J. The code rate for this figure is fixed at 20/64 (i.e., $k = 20$). This figure shows the conditional throughput versus the number of blocked bins J when the number of users with packets to transmit is $C = 100$. We see that $\beta = .45$ is approximately optimal when $J = 0$, and smaller values of β are optimal as J increases. Again, mismatch between β and J (for given k) can result in substantial performance loss. If dynamic control (with respect to interference level) is used, the indicated envelope (dashed line) is obtained.

So far we have concentrated solely on the potential benefits of dynamic control with respect to adapting β for the interference level J. FHMA has been shown to be ideal for supporting bursty traffic, since nearly the same communications capacity is present as compared to a constant number of continuously transmitting users [63]. However, to achieve this capacity, the transmission probabilities must be adjusted to account for the time-varying number of users with packets to transmit. This is illustrated in the next three figures. All three are based on the coding parameter choice $k = 22$ and no external interference.

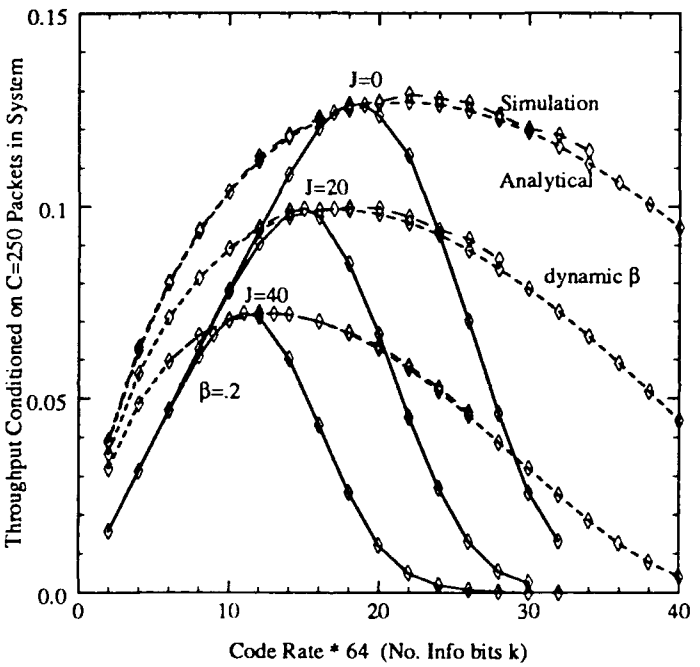

Figure 4.2: One slot throughput when number of stations with packets = 250 versus coding parameter k, static ($\beta = .2$) and dynamic control, various jamming levels.

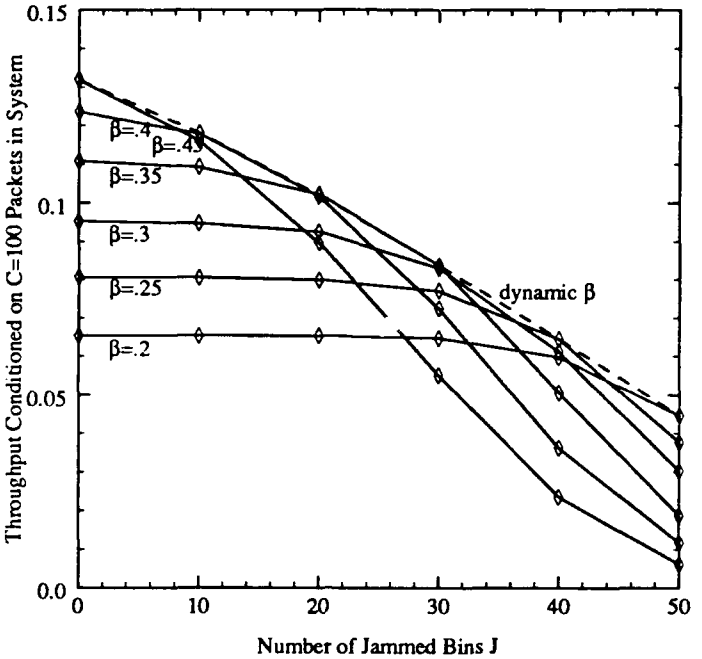

Figure 4.3: One slot throughput versus jamming level J when 100 stations have packets to transmit, $k = 20$, various β.

Figure 4.4 shows the conditional throughput versus the number of users with packets C for various values of β. Clearly, an optimum value for β occurs for each C; the resulting locus of optimal throughputs is shown as a dashed line. Note that the case $\beta = 1$ corresponds to the system of a constant number of users transmitting continuously, and the optimal throughput can be obtained using the results of Kim and Stark [61]. At the other extreme, as $C \rightarrow \infty$ the traffic tends to be Poisson, and the resulting performance can be obtained using (3.9) (the model of Ghez et al. [62]), and the optimal value of β is given approximately by (3.14).

Figure 4.5 presents the conditional probability that a transmitted packet will succeed versus the number of users with packets C, for various values of β. The dashed line indicates the values that correspond to the optimum throughput (the dashed line of Figure 4); note that they are all near .9, implying that once a packet is transmitted, it has a high chance of success (providing dynamic control is employed).

Figure 4.6 presents the symbol level performance as a function of network traffic conges-

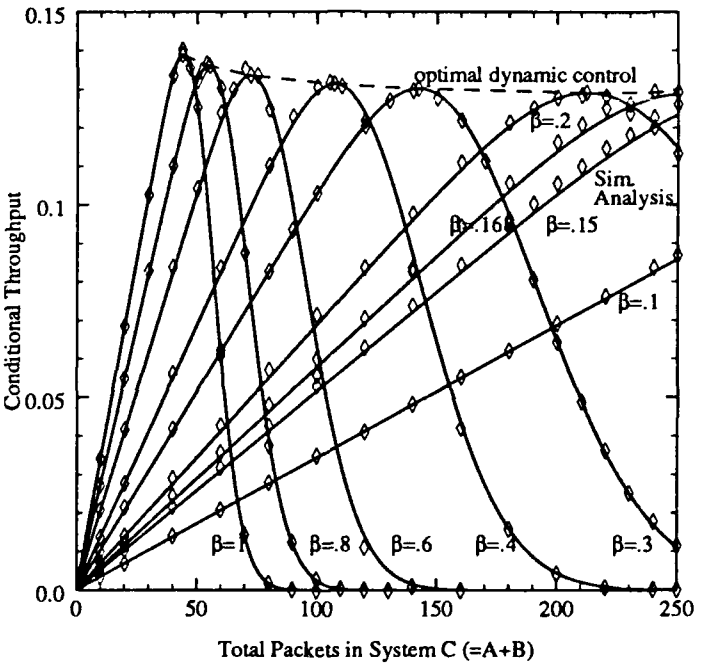

Figure 4.4: Conditional throughput versus number of users with packets, no jamming and $k = 22$ information symbols.

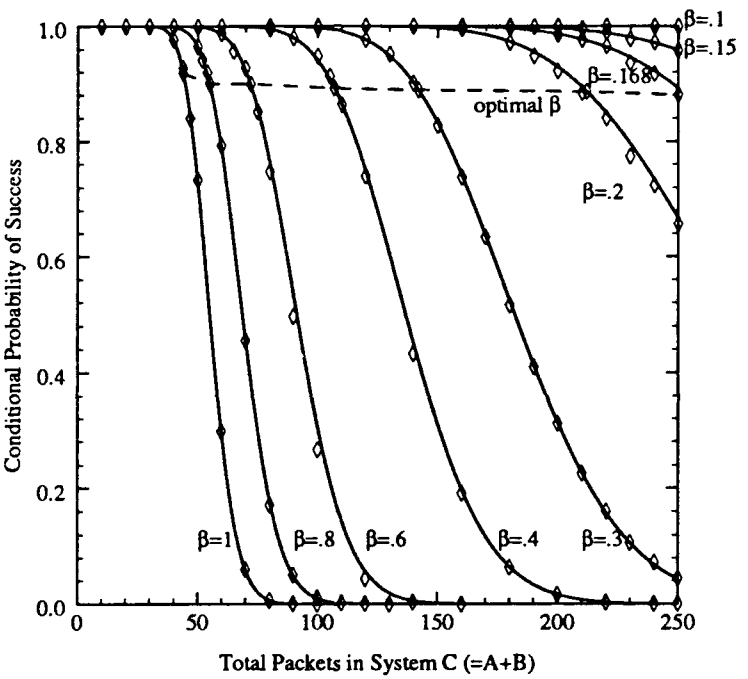

Figure 4.5: Conditional probability of success versus number of users with packets, no jamming, $k = 22$.

tion. The conditional probability that a transmitted symbol is hit (i.e., overlaps with one or more other symbols) is given versus the number of users with packets C, for various β values. Again, the dashed line indicates the performance when the optimal β is used.

The next two figures compare control schemes with respect to both the interference level and the varying network traffic congestion. Whereas all of the previous figures were based upon the performance conditioned on the number of users with packets to transmit in a particular slot, Figures 4.7 and 4.8 present steady state performance for the random access system with external interference, derived by analysis of the system Markov chain.

Figure 4.7is based on an arrival process with $\Delta = .2$. Both static control with $\beta = .2$ (fixed) and dynamic control policies are considered. Three different choices are made for each control type. These choices are based upon selecting the optimal parameters (maximum throughput) for the three possible interference levels $J = 0$, 20, and 40. Numerical searches identified the optimal code parameters k for the static ($\beta = .2$) cases to be $k = 30$ if $J = 0$, $k = 23$ if $J = 20$, and $k = 17$ if $J = 40$. For the dynamic control cases we found the optimal values are $k = 22$ if $J = 0$, $k = 17$ if $J = 20$, and $k = 13$ if $J = 40$. Figure 4.7 presents the performance for each of these cases as the interference level J is varied. This figure clearly illustrates the benefits of dynamic control over static control. We see that while the static control performance is good when the interference level is near the design value, substantial degradation occurs when J deviates from the value for which the parameter k was chosen. Dynamic control performance remains nearly optimal throughout the range of J; the case with $k = 17$ never deviates more than 13% from optimal over the entire range of J illustrated.

Figure 4.8 is similar to Figure 4.7 except that a more bursty arrival process is assumed, with $\Delta = .1$. Also, we investigate static control with the relatively high value of $\beta = .4$. We again numerically search for the optimal value for k for the six cases of the two control policy types at $J = 0$, 20, or 40. However, unlike the static control cases of Figure 4.7, we now find bistable behavior occurs for $\Delta = .1$, $\beta = .4$ when k and J are too large. Thus, for these cases, rather than optimizing with respect to throughput, we select the largest value for k (given J) that results in a drift that is zero at only one point. (This is one criterion that has been offered as an indication of stability.) When J is increased beyond the design value, bistability will occur, and performance will quickly degrade. Comparison of performance again shows that major benefits are obtained by employing dynamic control

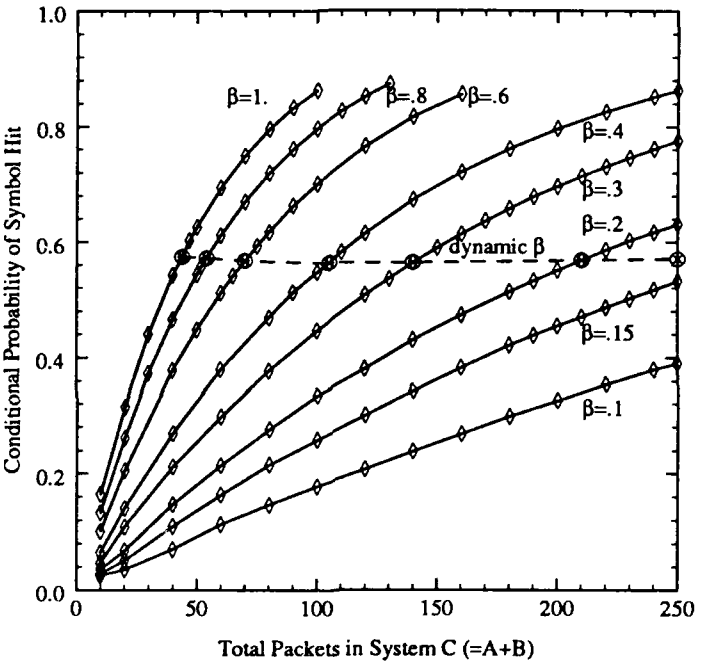

Figure 4.6: Conditional probability of symbol hit versus number of users with packets, no jamming, $k = 22$.

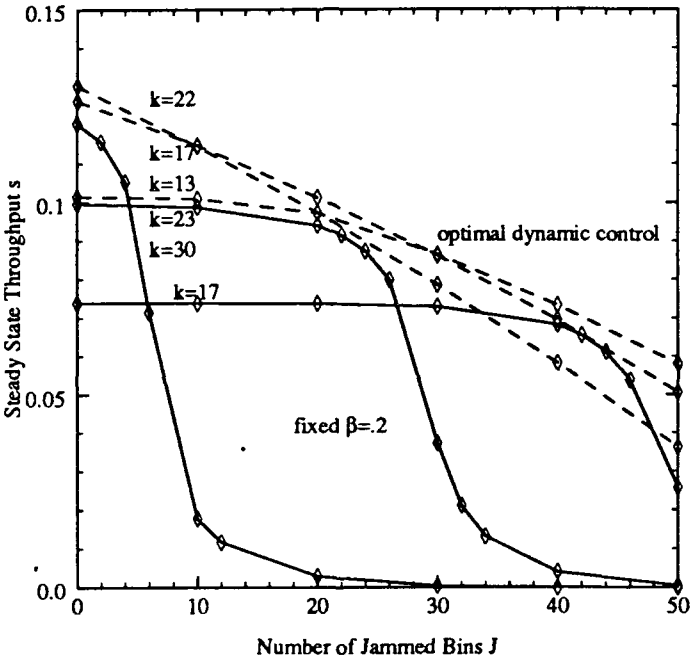

Figure 4.7: Steady state throughput s versus jamming level J, $\Delta = .2$, various control schemes and code rates.

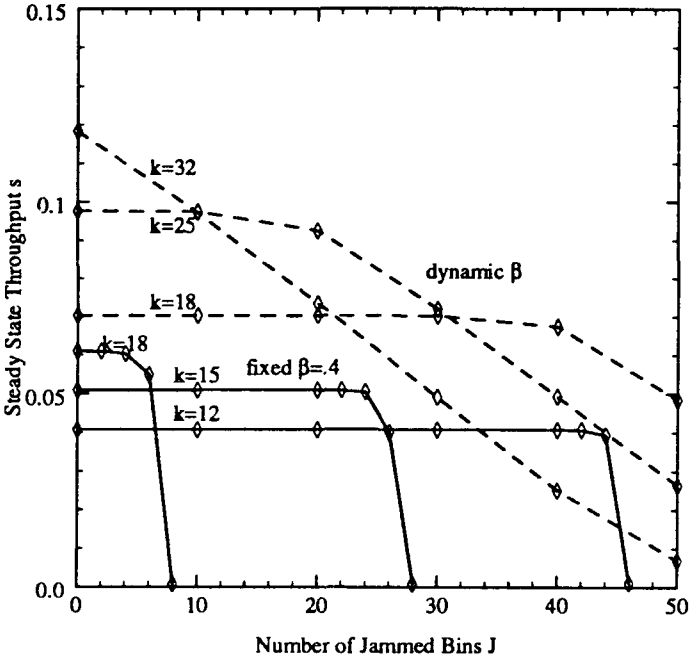

Figure 4.8: Steady state throughput s versus jamming level J, $\Delta = .1$, various control schemes and code rates.

procedures. Note that the increased variability caused by small Δ appears to indicate that adaptive code rates may provide significant benefit.

Figure 4.9 relates the conditional throughput (such as was depicted in Figure 4.3) to the unconditional throughput of Figure 4.7. The static control case with $\Delta = .2$, $\beta = .2$ and $k = 23$ is considered. The steady state throughput is redrawn from Figure 4.7 as a dashed line. The mean number in the system for this case when $J = 0$ was found to be $E(C) = 139.1$. As J is increased, the system becomes more congested, with $E(C) = 145.4$ at $J = 20$, and $E(C) = 249.5$ at $J = 50$. The conditional (single-slot) throughput is shown for the cases where the number of users with packets $C = 139$ and when $C = 250$. We see that the steady state performance falls roughly between the conditional curves, with a sharp drop occurring around $J = 30$ where the congestion suddenly becomes large. Thus, the decline in steady state throughput is more severe than might be concluded from a graph such as Figure 4.3.

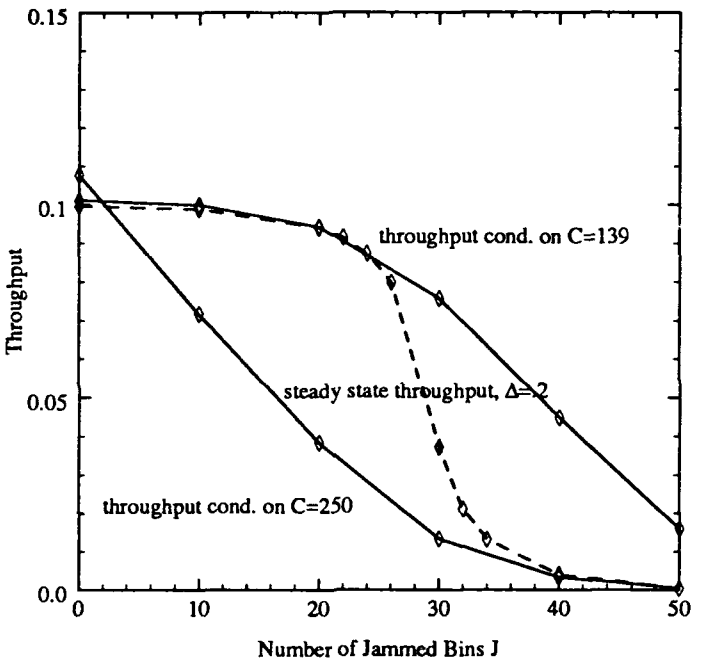

Figure 4.9: Comparison of conditional and steady state throughput versus jamming level J for static $\beta = .2$, $k = 23$.

4.4 Conclusions

A performance analysis of the effects of interference on transmission control policies for slotted ALOHA with frequency-hopped code division multiple access has been presented. Dynamic control has been shown to provide considerable performance improvements over static control. Performance has been evaluated using both analytical and simulation models.

Numerical examples illustrated the robustness gained through the use of dynamic control policies. Static control policies have been shown to achieve essentially equivalent performance as dynamic control schemes *provided that precise a priori knowledge of the interference level is known.* However, substantial degradation in performance occurs in the static controlled system if the interference level deviates from the presumed values used for tuning the system design parameters. No such sensitivity is present for the dynamic controlled case.

Chapter 5

Implementation of Dynamic Control

Abstract

Dynamic transmission control procedures are identified for single-hop slotted ALOHA networks using frequency-hopped spread spectrum for both code division multiple access and anti-interference. These control procedures are implementable, and do not require a "genie" as in earlier studies of such systems. Control is based on varying the probability of transmission as a function of the estimated network backlog (i.e., the number of users with packets pending). The backlog process is estimated by sensing activity on the receiver-based code while the user is not transmitting (half-duplex operation is assumed). The interference (ambient noise and/or jamming) is assumed to be statistically time invariant. Performance is derived by simulation and compared to a "genie" model that is derived by mathematical analysis of the underlying Markov chain. Numerical examples show that the feasible system operates at nearly the same level of performance as the "genie" model, and that considerable robustness exists with respect to the accuracy of a priori knowledge of the interference level. Numerous graphs illustrate transient response and steady state behavior.

5.1 Introduction

In the previous chapters we found that substantial improvements can be achieved by the use of dynamic control procedures. However, in those studies we assumed that a "genie" provided information to the users about the existing user congestion (backlog) and noise/jamming level. In this chapter we remove the "genie" artifice and demonstrate that dynamic control procedures are feasible. A practicable procedure for estimating the backlog is derived, and

numerical results provided by the simulation model indicate that performance nearly equal to that under the "genie" assumption is realizable. The noise/jamming level is assumed to be stationary, and an a priori estimate of this level is presumed to be known. Numerical results illustrate that performance is not highly sensitive with respect to the accuracy of the a priori knowledge.

5.2 System Model and Estimation Procedure

We assume that the system operates in a slotted fashion; this simplifies the derivation of the estimation procedures. The transceivers are assumed to be half-duplex, however, it is assumed that there is a sufficient receiver pool and traffic destination mix that the chance of two packets being simultaneously transmitted and destined to the same receiver is negligible. (We are therefore ignoring "topological competition" so that we may concentrate on the the random access aspects.) As before, each receiver listens on a different psuedo-random code sequence in which the next frequency bin is selected uniformly over the q bins.

The backlog estimation procedure will operate on the basis of feedback. The feedback obtained depends on the state of the user. Each user is either (1) actively transmitting a packet, (2) idle, with no packet pending transmission, (3) has a packet pending but is deferring transmission or retransmission according to the ALOHA protocol, or (4) is in the process of receiving a packet. Because of the emphasis on random access and its known benefits for bursty traffic, the users are presumably in states (2) or (3) (idle) a majority of the time.

In the following we provide details regarding the system model and derive the procedure for generating the backlog estimates. We begin by describing the procedure for the case when the user is neither actively transmitting nor receiving a packet.

An idle user will monitor the ether using his receiver-based code in order to form estimates of the channel activity. That is, individual samples are made from a single symbol dwell time at the frequency bin selected psuedo-randomly according to the specific user's receiver-directed CDMA code. Such a user will detect either "something" or "nothing," i.e., we assume binary channel feedback. Details of the physical implementation of the monitoring mechanism are outside of the scope of this work, but presumably has the form of an energy detector and threshold comparison. We assume that the feedback to the monitor is "something" if (1) one or more user transmissions overlap the monitored symbol-interval/frequency bin, (2) ambient noise exists that would have caused a symbol error if a single symbol had been transmitted exactly during this symbol-interval/frequency bin, *or* (3) the monitored frequency bin was jammed. We assume that the jammer is slowly time-varying, so that

partial jammer overlap within a symbol interval is not an issue. If none of the above three events occurs during the monitored symbol interval/frequency bin, then that sample's feedback is "nothing." Note that the receiver will not be able to distinguish between other user transmissions or interference (noise or jamming) when "something" is detected.

A transmitted symbol can be corrupted either by overlap with other user's transmissions (multiple access interference) or by "external interference" consisting of ambient noise and/or jamming. We will need to describe the system behavior from the perspectives of a user that is transmitting as well as a user that is idle and monitoring the ether. We define the following notation. Let $K_\ell^{ma} = 1$ denote the event that the ℓ^{th} symbol in a packet transmitted by a user suffers multiple access interference, and $K_\ell^{ma} = 0$ otherwise. We know that, because symbol transmissions among users are assumed to be asynchronous,

$$P(K_\ell^{ma} = 1|X) = 1 - (1 - \frac{1}{q})^{2(X-1)} \tag{5.1}$$

where X is the total number of users transmitting during the slot (we must have $X \geq 1$ here) and q = the number of frequency bins. Now consider a user that is monitoring the ether. Let $F_\ell^{ma} = 1$ if any of the X transmitting users overlaps the ℓ^{th} monitored symbol interval/frequency bin and $F_\ell^{ma} = 0$ otherwise. Then (for $X \geq 0$)

$$P(F_\ell^{ma} = 1|X) = 1 - (1 - \frac{1}{q})^{2X}. \tag{5.2}$$

We now characterize the external interference process. We assume that the ambient noise is stationary, and define

$$P_{\text{noise}} = \text{Probability of symbol error due to background noise.} \tag{5.3}$$

Furthermore, we assume that noise affects each symbol in a statistically independent fashion.

We assume a time-stationary jammer is present, and jams J of the q frequency bins. The jammer changes the bins that are jammed fast enough to prevent the user network from being able to avoid them, but slow enough to make partial symbol overlaps (as investigated in Chapter 2) negligible. For example, we may assume that the jammer selects a new jam band each slot. This model is similar to that of Chapter 4. We define

$$P_{\text{jam}} = \text{Probability of symbol error due to jamming.} \tag{5.4}$$

Since we assume that the jammer is stationary in the sense that J is constant, we have

$$P_{\text{jam}} = J/q. \tag{5.5}$$

We also define

$$P_I = \text{Probability of symbol error due to external interference} \tag{5.6}$$

where "external interference" is either background noise or jamming. We have that

$$P_I = 1 - (1 - P_{\text{noise}})(1 - P_{\text{jam}}). \tag{5.7}$$

Denote $K_\ell^I = 1$ as the event that the ℓ^{th} symbol transmitted by a user is corrupted by either ambient noise or jamming, and $K_\ell^I = 0$ otherwise. Similarly, let $F_\ell^I = 1$ denote the event that the ℓ^{th} symbol interval/frequency bin monitored by an idle user detects either ambient noise or jamming, and $F_\ell^I = 0$ otherwise. We have that

$$P(K_\ell^I = 1) = P(F_\ell^I = 1) = P_I. \tag{5.8}$$

The effects of either multiple access or external interference are combined as follows. Let $K_\ell = 1$ denote the event that the ℓ^{th} symbol transmitted by a user was unsuccessful, and $K_\ell = 0$ otherwise. Then

$$P(K_\ell = 1|X) = 1 - [1 - P(K_\ell^{ma}|X)][1 - P(K_\ell^I|X)] = 1 - (1 - \frac{1}{q})^{2(X-1)}(1 - P_I). \tag{5.9}$$

Similarly, let $F_\ell = 1$ denote the event that the ℓ^{th} symbol interval/frequency bin monitored yielded "something," and $F_\ell = 0$ if it yielded "nothing." Then

$$P(F_\ell = 1|X) = 1 - [1 - P(F_\ell^{ma}|X)][1 - P(F_\ell^I|X)] = 1 - (1 - \frac{1}{q})^{2X}(1 - P_I). \tag{5.10}$$

The assumptions implicit in the above formulas are that the monitor detects multiaccess, noise and jamming levels at exactly the same levels at which they cause interference to transmissions. The justification of these assumptions is strongly dependent on specifics of the physical implementation of the waveforms employed and receiver characteristics. Relaxation of these assumptions and sensitivity analyses are left as an area for future research.

We now proceed to derive the backlog estimation algorithm that uses this feedback and an a priori estimate of the interference level. We denote

$$\widehat{P_I} = \text{a priori estimate of } P_I. \tag{5.11}$$

As was indicated earlier, the system is assumed to operate in a slotted fashion. Each slot consists of L symbol intervals, and packet success and monitor feedback is accumulated

accordingly. Here we are considering the case where the user is idle, i.e., either has no packet pending or is deferring transmission in accordance with the ALOHA protocol. Such a user is idle for an integer number of slots, and updates his backlog once per slot. Since the system operation is stochastically stationary during a given slot, the feedback samples can be accumulated over each slot (sufficient statistic). We denote H^{mon} as the number of symbol interval/frequency bin samples that have "something" detected in them, so that

$$H^{mon} = \sum_{\ell=1}^{L} F_\ell, \tag{5.12}$$

$$E(H^{mon}|X) = LP(F_\ell = 1|X) = L[1 - (1 - \frac{1}{q})^{2X}(1 - P_I)], \tag{5.13}$$

where the latter equality holds because the F_ℓ are identically distributed for each ℓ (in the same slot).

We begin the backlog update procedure derivation by first estimating the number of users that must have transmitted given that H^{mon} hits out of L were detected. We form our heuristic estimate of X by first equating the given empirical statistic H^{mon} with the expected value as indicated by equation 5.13 above, with P_I replaced by the a priori estimate $\widehat{P_I}$:

$$H^{mon} \doteq L[1 - (1 - \frac{1}{q})^{2X}(1 - \widehat{P_I})]. \tag{5.14}$$

The estimate for X is then obtained by solving this equation for X in terms of the given feedback H^{mon}, obtaining

$$\widehat{X} = \frac{\ln(1 - H^{mon}/L) - \ln(1 - \widehat{P_I})}{\ln(1 - \frac{1}{q})}. \tag{5.15}$$

Next, we estimate the number of successes out of the $\widehat{X}$ that transmitted. If one of the transmitted symbols is selected at random, its chance of failing is estimated as

$$\widehat{P_{K=1,X}} = 1 - (1 - \frac{1}{q})^{2(\widehat{X}-1)}(1 - \widehat{P_I}). \tag{5.16}$$

The mean number of erasures in one of the $\widehat{X}$ transmitted packets is taken to be a binomially distributed random variable with parameters L and $\widehat{P_{K=1,X}}$. Since we are using an extended Reed-Solomon code with k information symbols, and perfect side information is assumed, the probability that a packet succeeds is the probability that the number of erasures is no

more than $L - k$. We also know that the success probabilities of different packets in the same slot (conditioned on X) are well approximated as being independent. Therefore, the expected number of successes, $\hat{S}$, is

$$\hat{S} = \hat{S}(\widehat{X}) = \widehat{X}P(Y < L - k), \tag{5.17}$$

where Y is binomially distributed with parameters L and $P_{\widehat{K=1,X}}$. If L is large, Y can be approximated as a Gaussian r.v., so that

$$\hat{S} = \hat{S}(\widehat{X}) = \widehat{X}\Phi\Big(\frac{L - k - \mu}{\sigma}\Big), \tag{5.18}$$

where $\Phi(\cdot)$ is the standard Gaussian cumulative probability distribution function, $\mu = LP_{\widehat{K=1,X}}$, and $\sigma = \sqrt{LP_{\widehat{K=1,X}}(1 - P_{\widehat{K=1,X}})}$. (Since precision is not needed in the update algorithm, a simple approximation may be used for $\Phi(\cdot)$ in implementing the backlog estimation procedure.)

Finally, the backlog estimate $\hat{B}$ is updated by adding the expected number of new packets to transmit $(N - \hat{B})\Delta$ and subtracting the estimated number of successes:

$$\widehat{B_{t+1}} = [\widehat{B_t} + (N - \hat{B})\Delta - \hat{S}]^+, \tag{5.19}$$

where $[\cdot]^+$ denotes $\max(\cdot, 0)$.

Some minor comments for implementation of this estimation algorithm follow. First, if $X = 0$ then we would still expect to detect energy due only to the interference, causing a mean number of detections $E(H^{mon}|X = 0) = LP_I$. We may first test whether the feedback H^{mon} is less than $L\widehat{P_I}$, and if so, estimate $\widehat{X} = 0$ and hence $\hat{S} = 0$. Also, there is small range of values of H^{mon} that can result in $0 < \widehat{X} < 1$, and this can cause problems when $\widehat{X} - 1$ is used as an exponent. In this case, we should estimate $\widehat{X} = \hat{S} = 1$. Finally, for large values of H^{mon} it is possible to obtain overly large estimates for X; we should always ensure $\widehat{X} \leq N$, where N = the total number of users. In particular, the unlikely case $H^{mon} = L$ will cause numerical problems (viz., $\ln(0)$) if not tested for.

The above procedure specifies the backlog update procedure for users while they are idle. However, the backlog estimate must also be updated when either the user is transmitting a packet or receiving a packet. In our studies, we have made the common assumption that feedback regarding the success of a transmitted packet is obtained immediately at the end of the transmission. Also, we have not been concerned with what has been termed "topological competition," namely the contention resulting from finite receiver capabilities. In essence, we have assumed that receiver resources do not present a significant bottleneck. This would

correspond, for example, to the case where there are many more receivers than transmitters. However, it is intuitive that the action taken by a user that receives a packet should be similar to the action taken by a user that just transmitted a packet (and obtained immediate feedback as to its success). The simple backlog update policy that we have incorporated into our simulation is:

1. If the packet was successful, then it is likely that all X packets were successful. The value of X is estimated to be β times $\hat{B} + (N - \hat{B})\Delta$, where $\beta = \beta(\hat{B})$ is computed so as to cause $X = G$ if there is sufficiently many users with packets (i.e., $\hat{B}$ is large enough). Therefore, the backlog estimate is updated as $\widehat{B_{t+1}} = [\widehat{B_t} + (N - \widehat{B_t})\Delta - G]^+$.

2. If the packet was unsuccessful, then it is likely that all X packets were unsuccessful. Following similar logic as above, the backlog estimate is updated as $\widehat{B_{t+1}} = \widehat{B_t} + (N - \widehat{B_t})\Delta$.

This concludes the derivation of the backlog estimate algorithm. In the next section we present numerical results for simulations for a network of users employing the backlog estimation procedure coupled with the dynamic control algorithm that was developed in earlier chapters.

5.3 Numerical Results

In this section we present performance results that were obtained from our simulation model. The backlog estimation algorithm derived in the previous section was modeled in the simulation, and utilized together with dynamic control procedures derived in earlier chapters. Fully distributed control is employed; since each user perceives the environment differently because each user is using a different CDMA code, the users will typically have somewhat different backlog estimates. We note that such a system has a dimensionality approximately equal to the number of users in the network, thereby making direct mathematical analysis intractable. When the "genie" model is used, all users have the same estimates and the model is mathematically tractable (although still involving a large state space). The static control models are also amenable to mathematical analysis.

We have fully validated the simulation model by comparing its results under "genie" or static control assumptions with those of the mathematical analytical model that was described earlier. In addition, rigorous software engineering discipline was adhered to, with numerous validation tests performed with each increment in its development. In the interest of clarity and brevity, we do not present these comparison test results; the simulation

essentially always agreed very well with the analytical model. In the following, we limit the simulation results to the practicable scheme as described in this chapter; these are identified as "real" results. Some analytical results are provided for the "genie" model and are identified accordingly.

As in previous chapters, we assume that the network consists of $N = 250$ users, $q = 100$ frequency bins are used, packets have a length of $L = 64$ symbols, and DFT ALOHA is employed.

Figure 5.1 presents a comparison of throughput performance for "genie" and "real" schemes. The parameter assumptions are identical to those used in creating Figure 3.8. Steady state normalized information throughput is plotted versus the arrival rate while in the thinking state per user. Three dynamic control cases are considered, based upon the simple control function given by equation (3.17): $G = 50$ and $k = 19$, $G = 25$ and $k = 32$, and $G = 75$ and $k = 11$. We see that the performance of the feasible ("real") control system is very close to that of the "genie" model over wide ranges of parameters. This is the first indicator that tells us that the advantages of dynamic control (stability and robustness) are truly obtainable. Also, since we cannot do better than the "genie" model, this tells us that it is not worthwhile expending effort in enhancing the backlog update procedure with greater precision.

Figures 5.2 and 5.3 provide additional steady state performance characterization for the same cases as Figure 5.1. Figure 5.2 illustrates the mean number of transmissions per slot (which should equal G when there is sufficient load on the network), while Figure 5.3 presents the mean true backlog. Again, we see that "real" and "genie" models perform similarly.

Figure 5.4 illustrates steady state throughput performance in the presence of jamming. The figure is similar to Figure 4.7, however, there the "genie" not only told the users what the backlog was, it also told them what the level of jamming was, and therefore allowed the users to optimally alter the G value. In Figure 5.4 the G value is assumed to be fixed, as well as the number of information symbols per packet k. Three cases were run: $k = 13$ and $G = 42.2$ (optimal if $J = 40$), $k = 17$ and $G = 43.3$ (optimal if $J = 20$), and $k = 22$ and $G = 42.1$ (optimal if $J = 0$). Each of these were run for "genie" and "real" cases, where as usual in the "genie" case the backlog was known to all users. In the "real" cases, the backlog update was based upon feedback and the use of $\widehat{P_I}$, where $\widehat{P_I}$ was fixed at .4, .2 and 0 for the tree cases respectively. Therefore, these results indicate the relative insensitivity to a priori knowledge of the interference level.

The remaining figures investigate the performance in the presence of a time-varying arrival rate. These illustrate the transient behavior when sudden changes in system characteristics occur, and also provide an indication as to the benefit of devising additional algorithms for tracking such time-varying course-grain parameters.

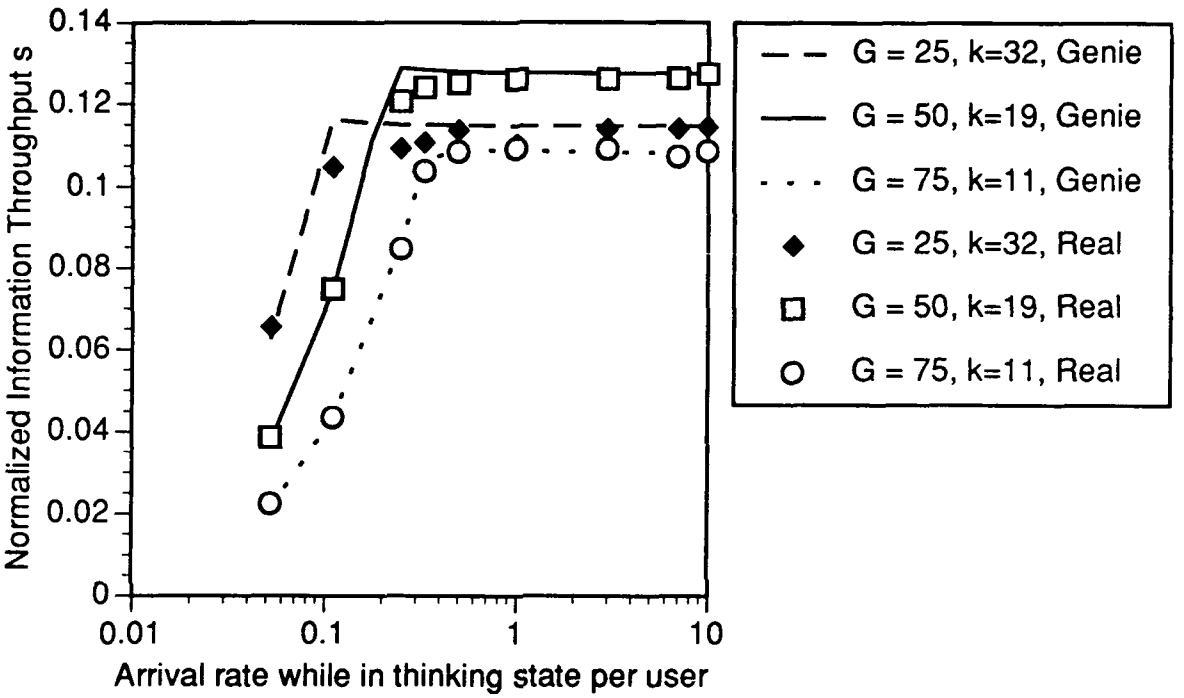

Figure 5.1: Steady state throughput s versus arrival rate η, "genie" and real cases

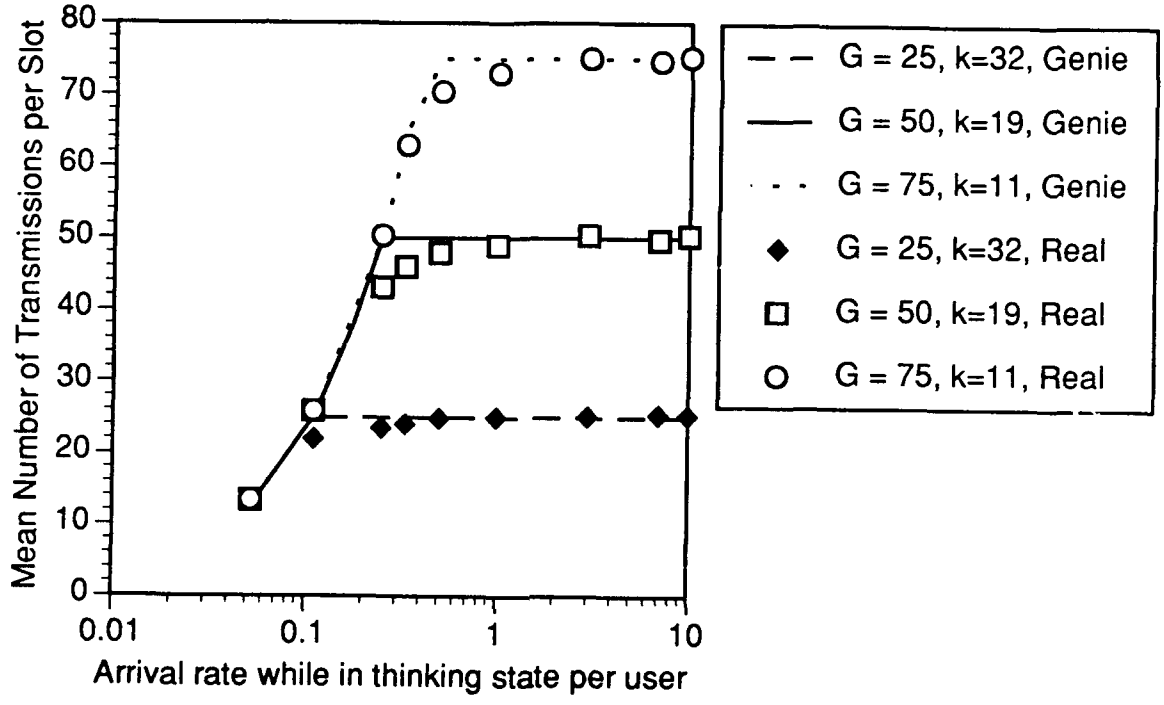

Figure 5.2: Steady state mean number of transmission per slot $E(X)$ versus arrival rate η, "genie" and real cases

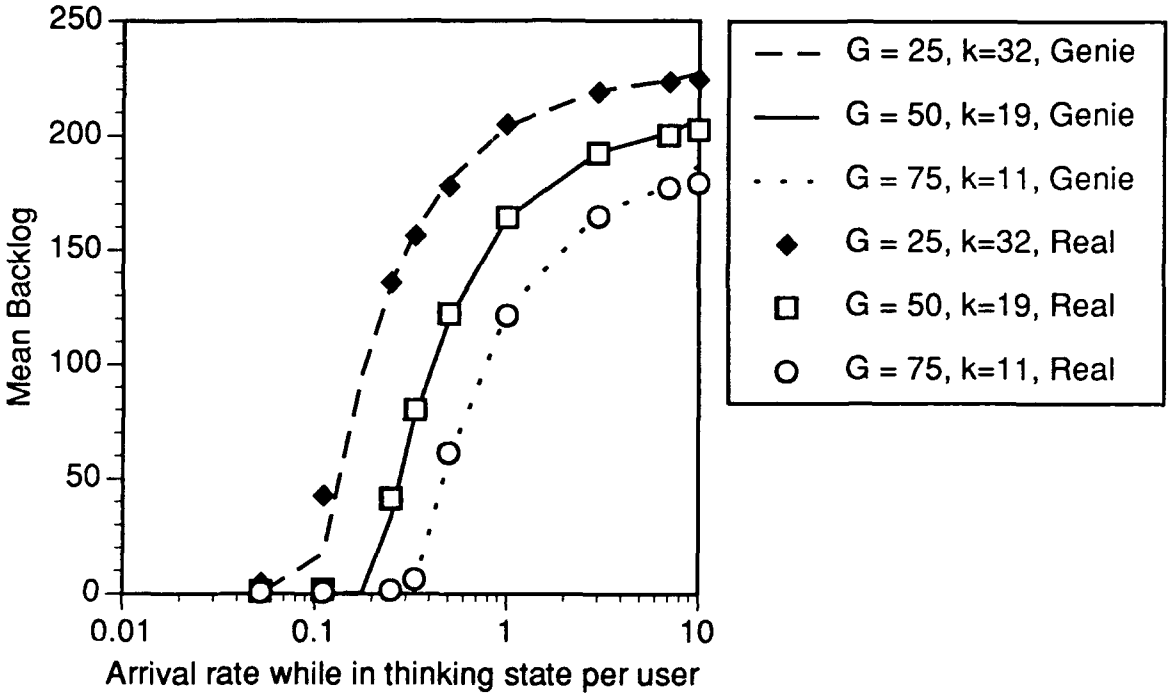

Figure 5.3: Steady state mean backlog $E(B)$ versus arrival rate η, "genie" and real cases

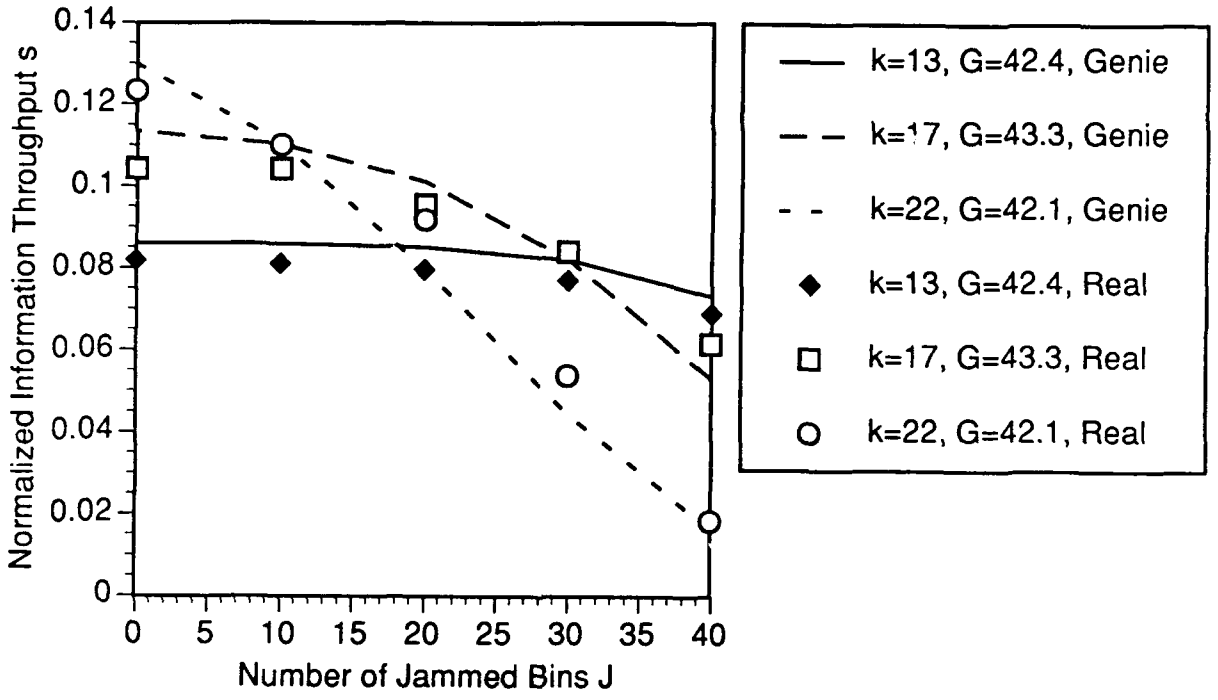

Figure 5.4: Throughput s versus number of jammed bins J for "genie" and "real" cases

We incorporated a Markov-modulated arrival process into our simulation model. (This was also included in the analytical model but time prevented us from exercising it.) A slowly time-varying two-state Markov chain alternated between states independently of the other system behavior. The arrival rate of all users in the thinking state would take on one of two values according to the value of the background Markov chain. In the results presented below, we let the arrival rates for the two states be $\eta = 1/9$ (corresponding to $\Delta = .1$) and $\eta = \infty$ (corresponding to $\Delta = 1$), so that the arrival rates alternated between rather extreme values. These were intentionally selected so as to exaggerate the performance impacts.

The simulation model also was made to have a "semi-genie" model selectable, in which the genie would tell the users when the arrival rate changed but nothing else. In the "real" case there was no such genie, and a constant a priori estimate of the arrival rate $\widehat{\eta}$ was used.

Figure 5.5 illustrates the performance obtained for the "semi-genie" model. This shows the true backlog and the estimated backlog as a function of time, measured in slots. The estimated backlog values are averaged over all users for each given slot. We see that the estimate is quite good, and both the true and estimated backlog react quickly to transients. The normalized information throughput for this run was $s = .0558$.

Figure 5.6 shows a similar plot but where no genie information is provided. The a priori estimate of the arrival rate is taken to be the constant $\widehat{\eta} = .163$ ($\widehat{\Delta} = .14$). We see that for this value of $\widehat{\eta}$, the backlog is apparently over- and under-estimated roughly equally. The normalized throughput that resulted from this run was .0388, or about 70% of that achieved with the semi-genie model.

Figure 5.7 shows the true and estimated backlog processes for the case when $\widehat{\eta} = 1.86$) ($\widehat{\Delta} = .65$). Although the backlog is poorly estimated during the intervals of low arrival rates, the resulting normalized throughput obtained was .0415, which is somewhat better (about 74% of semi-genie) than that achieved for the case of Figure 5.6. We ran simulations for the entire spectrum of values for $\widehat{\eta}$, and generally found little sensitivity to the value selected. We conclude that, for the case considered, some benefit may be possible by devising algorithms for tracking the gross arrival rate, but this benefit is not major. (Recall the exaggerated arrival rate extremes.) Given that a constant value is used, it is not especially sensitive the value selected. We emphasize that these conclusions may or may not be extendable for all parameter settings, and further analysis should be made for specific network designs.

5.4 Conclusions

In this chapter we have developed implementable dynamic transmission control procedures for single-hop slotted ALOHA networks using frequency-hopped spread spectrum. These

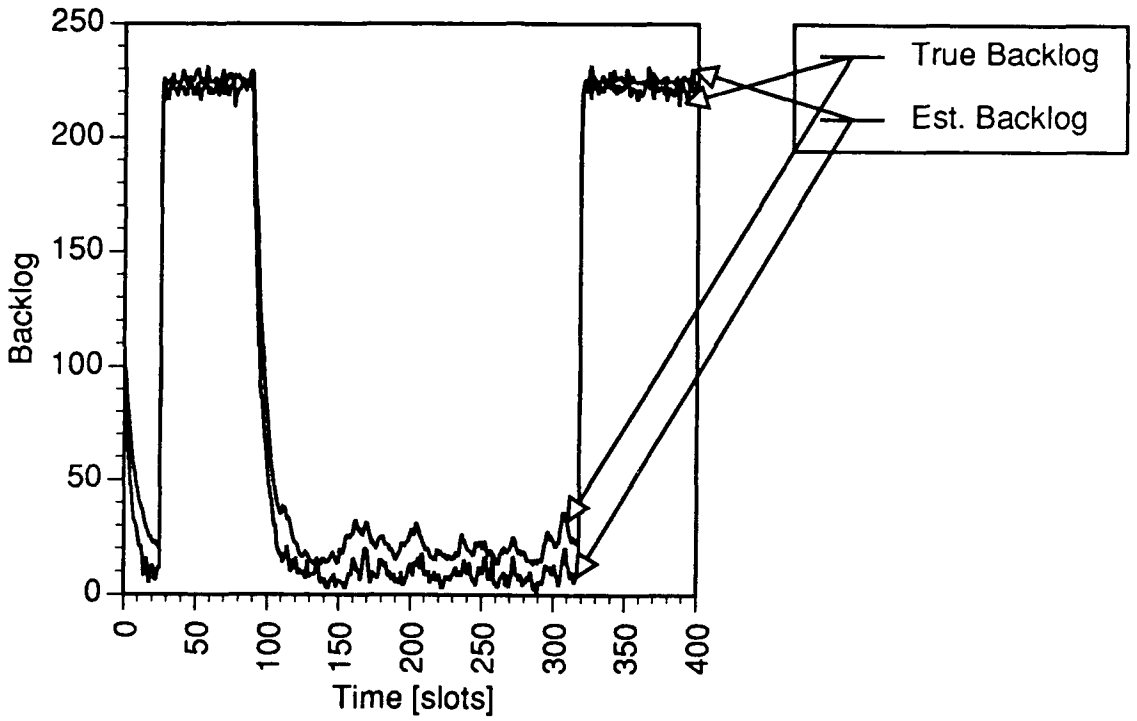

Figure 5.5: True and mean estimated backlog versus time, $\eta = \hat{\eta}$ alternating between 1/9 and ∞ ("semi-genie")

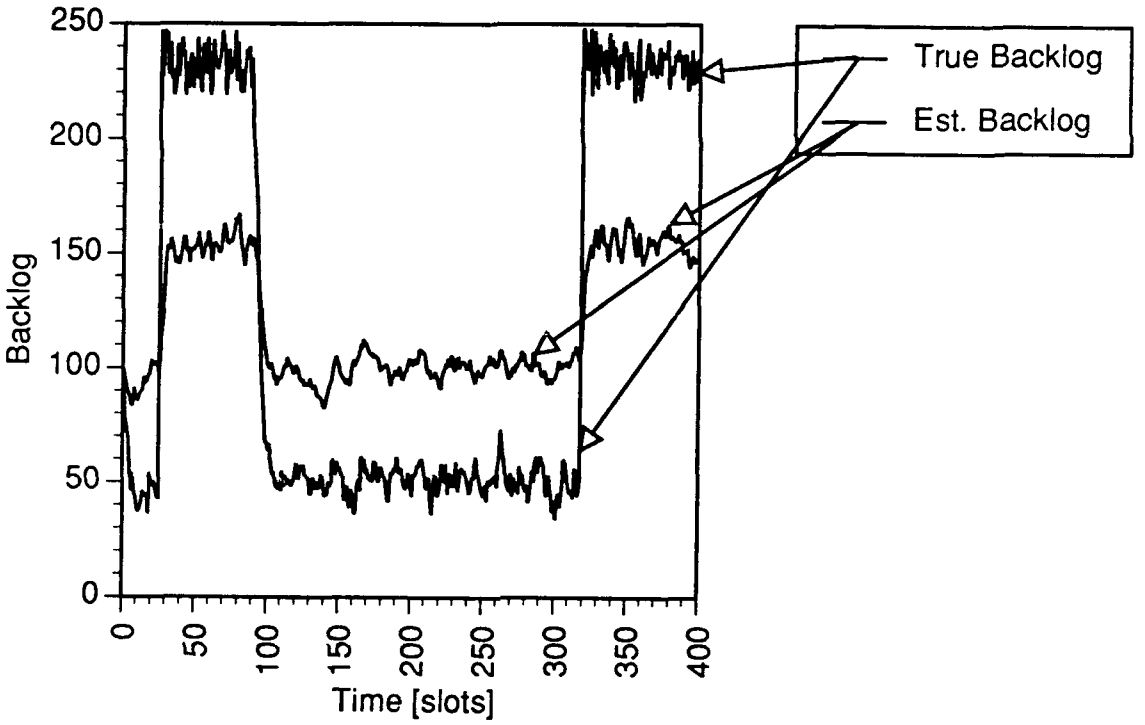

Figure 5.6: True and mean estimated backlog versus time, $\hat{\eta} = .136$

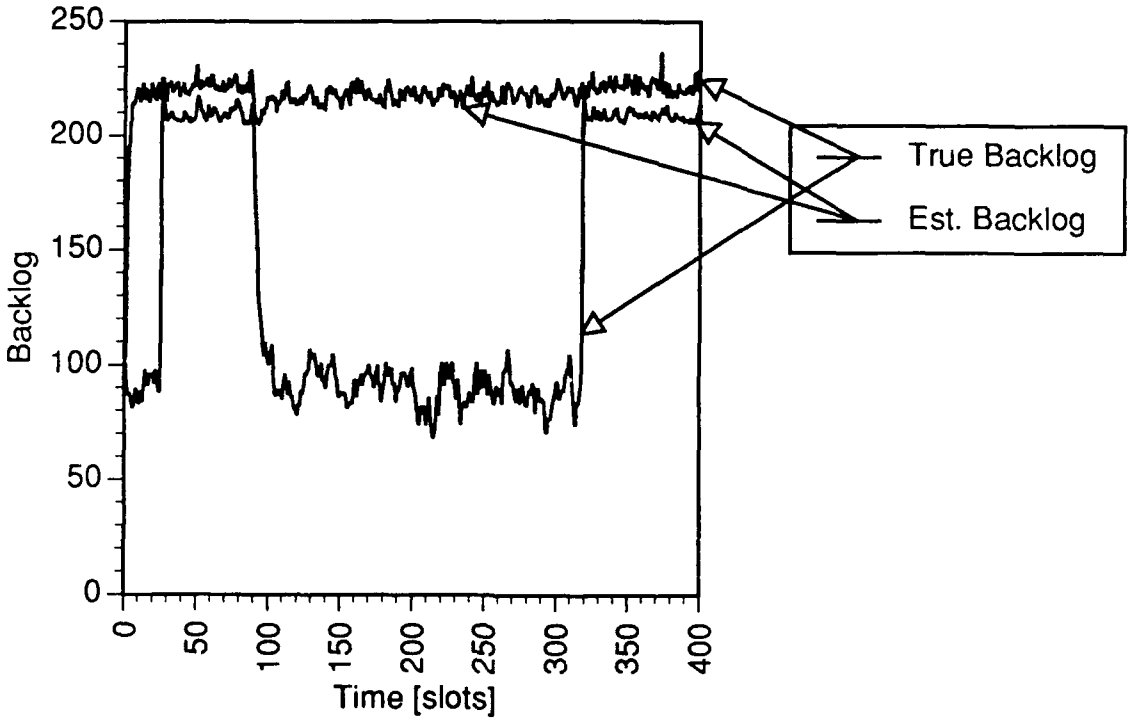

Figure 5.7: True and mean estimated backlog versus time, $\hat{\eta} = 1.86$

control procedures are based upon backlog estimates, and a backlog estimation algorithm was derived that operates in the presence of multiuser interference, ambient noise, and jamming. The backlog process is estimated by sensing activity on the receiver-based code while the user is not transmitting (half-duplex operation is assumed), so that minimal (if any) additional hardware is required. Performance was derived by simulation, and numerical examples show that the feasible system operates at nearly the same level of performance as the "genie" model. These results demonstrate that considerable robustness is achievable.

Chapter 6

Concluding Remarks and Future Plans

The communications needs for SDI involve survivable interconnections of a large number of nodes in both space and on ground with highly transient traffic characteristics and processing loads. The combined multiple access properties of random access protocols together with spread spectrum techniques appear to be very attractive for meeting such SDI needs, as random access is very efficient at light traffic loads while spread spectrum smoothens the impact of congestion when traffic increases rapidly and provides anti-jam protection in addition to low probability of interception. While substantial amount of work is done by various researchers during the past two decades on both the unspread random access and on physical channel aspects of spread spectrum such as rapid code acquisition, modulation formats, filter and receiver structures, and estimation of probability of errors, very little has been done on link and network level protocol issues involved on a system that combines random access and spread spectrum schemes.

During the past three years we have made substantial progress in our investigations on this emerging topic under this contract. We have addressed such fundamental issues as comparison of slotted and unslotted schemes, control policies for stable operation, and performance evaluation under different jamming scenarios. We have shown convincingly through analysis and simulation that there is very little to be gained in using time slotting compared to unslotted operation. Though in the unspread ALOHA schemes, it is well known that slotting doubles the maximum throughput due to reduction in the loss of channel time due to collisions, this difference in the performance in the slotted and unslotted operation is almost completely erased in the spread case due to the recovery of the majority of collided packets. This is very important since slotting involves time coordination of all the participating nodes

and should be avoided if possible. We have also shown that such systems are less sensitive to the degree of burstiness. We developed and analyzed a dynamic control procedure for stability that uses a backlog-dependent transmission rate and showed that a dynamic control policy is less sensitive to arrival rates than static control policies. Further, we evaluated both the control policies under different conditions of jamming. We have also developed robust procedures for implementation of the dynamic control policies that do not require a "genie" to assist in backlog estimation and evaluated these implementation procedures. The above results have been reported in three papers and a fourth paper is in preparation.

Proposed Future Work

Based on the framework created by the current work, we propose further work on several important issues such as (1) Comparison of Direct Sequence and Frequency-Hop Systems, (2) Vulnerability Analysis of Control Policies, (3) Multi-hop operation. Our approaches to investigating these issues are briefly given below.

1. **Comparison of Direct Sequence and Frequency-Hop Systems**

   Spread-spectrum–random access schemes can be implemented using either direct sequence (DS) or frequency hopping (FH) approach or a combination of the two, i.e., hybrid DS/FH. When each receiver is assigned a unique pseudo random (PN) sequence to realize a DS or FH based multiple access operation, the resulting scheme is known as a Code Division Multiple Access (CDMA) scheme. The code set is to be chosen to meet low crosscorrelation and high autocorrelation requirements. In our previous analyses we chose FH methodology. In a DS system, a transmitter uses a large bandwidth (based on the processing gain, ratio of the rate of the spreading code to the rate of information) in each transmission. This will require wideband transmitters and receivers. In a FH system, transmissions need a relatively narrower bandwidth that depends on information rate but a frequency synthesizers and filters are needed at the transmitters and receivers capable of providing a large number of frequencies for hopping (depending on the desired spread factor). For a given application, a number of factors need to be considered before selecting either DS or FH operation. For example, when multipath fading is involved, DS systems offer an advantage as they can distinguish unwanted out-of-phase signals by locking on to only one of the signals. On the other hand, FH signals, being narrowband signals can be designed for use at higher signal-to-noise ratios with some error correction for protection against frequency hits.

It is not clear whether DS or FH is superior for spread spectrum random access schemes. Indeed, there are no available criteria to compare them in a general way, except by taking a candidate system depending on the desired application and develop comparative results specific to that system. While intuitively it appears that under similar power and bandwidth constraints, both DS and FH may exhibit similar intrinsic potential, from an implementation point of view, a number of factors may play a key role in their selection such as backlog estimation for dynamic control, nature of ambient noise and interference, type of jamming, allowed packet sizes and the minimum overhead needed for code synchronization, etc. We will develop analytical and simulation models for DS and FH incorporating these features and evaluate their relative performance using realistic parameters in the context of random access applications. We will also investigate and quantify the characteristics of hybrid DS/FH systems.

2. **Vulnerability Analysis of Control Policies**

Our research on slotted ALOHA with frequency-hopped code division multiple access has demonstrated that dynamic retransmission control provides very robust performance in the face of variations in packet arrival rates, code rates, and partial or wideband jamming. However, it is possible that using a "smart" dynamic control policy will make the system vulnerable to spoofing or intelligent jamming. We propose to investigate the vulnerability of dynamic retransmission control policies to intelligent jamming. Specifically, we will investigate whether it is possible for an adversary to use knowledge of the dynamic retransmission control policy to develop clever jamming procedures which exploit the control policy and thus degrade system performance beyond the amount of degradation which would be caused by a simple partial band or wideband jammer at the physical transmission level. If such procedures exist, we will examine the measures needed to protect the control policies. This is in many ways analogous, at the link and network levels of the communication stack, to the use of spread spectrum to defeat jammers at the physical level that are smart enough to scan for narrowband signals.

3. **Multi-hop Spread Spectrum Networks**

We propose to extend our work to multi-hop networks, where the topology is not assumed to be fully connected. Different aspects are emphasized than in single-hop SSRA systems. For example, the number of neighbors per user is typically relatively small, so that there is less concern for multiuser interference, but the implications of half-duplex operation and buffering behavior are more profound. Deterministic TDMA scheduling algorithms have been investigated in the literature for spread spectrum

networks (with complete or partial tolerance of secondary conflicts). However, these algorithms generally assume that the complete topology and traffic flow requirements are known and fixed. Although there has been some advances in forming distributed scheduling algorithms for unspread systems, there remains a great need for developing transmission protocols for dynamic (traffic and topology) spread spectrum multi-hop networks. We propose to develop hybrid random access/TDMA protocols that can adaptively adjust the transmission rates and routes to accommodate the unpredictable variations expected in military (SDI) environments. Efficiency, simplicity and speed is achieved through the use of appropriate TDMA schedules, while the random access elements allow dynamism in the system and fast dissemination of control information needed to maintain the optimum TDMA schedules.

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